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19. ABSTRACT (Continue on reverse if necessary and identify by block number) Observations of solar active regions with the Very Large Array (VLA) have led to new information about the origin and prediction of explosive bursts, or flares, that can directly interfere with high-flying aircraft or disrupt communications with them. We have shown that energetic particles and radiation are expelled during explosive bursts from coronal loops. Several new insights to these exploding loops have been provided using the VLA together with supporting observations with the Solar Maximum Mission (SMM) satellite and the Nancay Radioheliograph (NR). The VLA uniquely provides spatial resolution at radio wavelengths, while the SMM gives X-ray data and the NR provides resolution in time and frequency. These observations have been carried out from 1983 to 1988, inclusive, with the support of grant AFOSR-83-0019.			
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The research carried out under the support of grant AFOSR-83-0019 has used all three instruments, the VLA, the SMM, and the NR, to study the quiescent, or non-flaring, emission from coronal loops, (Section II), radio bursts from coronal loops, (Section III), and radio bursts from nearby stars, (Section IV).

The ubiquitous coronal loops dominate the structure of the solar corona. They were first observed with expensive X-ray telescopes lofted above the Earth's atmosphere, but we have now shown that coronal loops can be observed with the ground-based VLA (Section A). Multiple wavelength VLA observations specify the three dimensional structure of solar active regions, (Section B); they uniquely specify the strength, evolution and structure of the magnetic fields in coronal loops, while also providing constraints on the density and temperature of the energetic plasma trapped within them.

Thermal cyclotron lines provide a sensitive measurement of the coronal magnetic field, (Section C), while comparisons with simultaneous SMM X-ray observations delineate the various radiation mechanisms, (Section D). Some coronal loops emit gyroresonant radiation that is detectable with the VLA, but these loops are invisible at X-ray wavelengths. VLA observations at long radio wavelengths reveal large-scale coronal loops that may be related to filaments and/or coronal mass ejections (Section E).

The VLA observations have provided important data on the preburst heating and magnetic interaction that trigger explosive bursts from coronal loops (Section F), while also showing that the energetic particles are accelerated and released near the apex of these loops (Section G). Small-scale, compact loops appear to be continually rising and bursting apart, thereby providing energy that may heat the the solar corona (Section H). The continued excitation of solar noise storms takes place in more extended, higher magnetic loops that connect active regions with more distant areas on the Sun (Section I).

Thus, all forms of solar bursts apparently originate in coronal loops of different sizes or scales, and then travel to the near-Earth environment where they can endanger aircraft or satellites. VLA observations of preburst heating and magnetic triggering of eruptions within coronal loops have particularly important implications for forecasting and understanding these forms of solar activity.

Observations of radio bursts from nearby active stars provide new perspectives to studies of explosive activity on the Sun. Rapid variations (Section J) and narrow-band structure (Section K) in stellar radio bursts require coherent radiation mechanisms (Section L) that may be important for some types of activity on the Sun.

The thirty-eight (38) papers published during 1983 to 1988, inclusive, are listed in Section V; they all acknowledge support from grant AFOSR-83-0019. The publications appear in the most reputable journals, including the Astrophysical Journal, Astronomy and Astrophysics, Science, and Solar Physics, as well as the proceedings of various workshops such as Advances in Space Research-Proceedings of COSPAR. These papers have been reproduced in Section X, an Appendix that has been sent under separate cover because of its length.

The twenty-five (25) papers presented at professional meetings and workshops in 1983-1988, inclusive, are delineated in Section VI. They include three meetings of the American Astronomical Society, three meetings of the Committee on Space Research (COSPAR), three NASA workshops associated with the Solar Maximum Mission (SMM) satellite, two European conferences, one meeting of the International Astronomical Union (IAU), and one meeting of the Union Radio Scientifique International (URSI). Papers discussing the research carried out under grant AFOSR-83-0019 have been presented in Finland, India, Italy, France and Russia; these have usually been invited lectures with no expense to the AFOSR.

Altogether we have proposed twenty-eight (28) VLA observational programs. The abstracts for these proposals are given in the Section VII. They have all been accepted and carried out during 1983-1988, inclusive, under the support of grant AFOSR-83-0019. Our proposals to use the VLA have never been rejected, primarily because of our strong record in publishing unique scientific results.

The VLA proposals abstracted in Section VII include observations of the quiescent and explosive radiation from coronal loops, with an emphasis on thermal cyclotron lines, current-amplified magnetic fields, the strength and structure of the coronal magnetic field, preburst heating, and the magnetic triggering of solar bursts. They also focus on the initiating and driving mechanisms for noise storms, Type I bursts, Type III bursts and coronal mass ejections. Solar jets, microflares and compact, variable sources are mentioned as possible sources for coronal heating. Explosive phenomena on nearby stars other than the Sun have also been studied, with an emphasis on coherent radiation mechanisms and a search for microwave emission from stars of late spectral type, magnetic stars, and contact binaries. The VLA observations of the Sun have been carried out with simultaneous observations with the Solar Maximum Mission (SMM) satellite and the Nancay Radioheliograph (NR), as well as other space-borne and ground-based facilities, thereby enhancing the scientific return of the research supported by grant AFOSR-83-0019, with no added cost to the grant.

The facilities used in performing the research presented in this report are described in Section VIII. The main research facility is the Very Large Array (VLA), a system of 27 antennae spread over a desert in New Mexico at separations as large as 34 kilometers. Simultaneous supporting observations have been carried out using the Solar Maximum Mission (SMM) satellite at X-ray wavelengths and the Nancay Radioheliograph to obtain high radio resolution in time and frequency. The cost of building and operating these facilities has been met by other institutions, including NASA, the NSF and the French government. Grant AFOSR-83-0019 has provided the important salary, travel and publication costs for the two Tufts scientists who have obtained, analyzed and compared the data, thereby producing a high scientific return at relatively low cost.

The relevance of this research to the United States Air Force is discussed in Section IX. We have provided a variety of new insights to explosive solar phenomena that generate energetic particles and radiation. They travel to the near-Earth environment where they can interfere with surveillance operations, disrupt tracking communications, and degrade or endanger high-flying aircraft, missiles, or satellites.

Reprints of the thirty-eight (38) papers published under the support of grant AFOSR-83-0019 have been bound together and submitted under separate cover as Section X, an Appendix.

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VERY LARGE ARRAY OBSERVATIONS OF THE SUN WITH RELATED OBSERVATIONS USING THE

SMM SATELLITE

GRANT AFOSR-83-0019

Final Technical Report
for 01 Jan. 1983 to 31 Aug. 1988

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I. INTRODUCTION

This is the final technical report for grant AFOSR-83-0019 entitled VERY LARGE ARRAY OBSERVATIONS OF THE SUN WITH RELATED OBSERVATIONS USING THE SMM SATELLITE for the period 01 January 1983 to 31 August 1988. During this time we have used the Very Large Array (VLA) to gain new insights into solar active regions and the powerful explosions that erupt from them. This research has practical implications in predicting and understanding the emission of energetic particles that perturb the aerospace environment and disrupt or interfere with satellites and high-flying aircraft.

Our report is divided into three main sections dealing with quiescent, or non-flaring, coronal loops, radio bursts from coronal loops, and radio bursts from nearby stars. The ubiquitous coronal loops dominate the structure of the solar corona. Magnetic energy is stored within them, and suddenly released during explosive bursts that occur near their tops. Studies of radio bursts from nearby stars have provided new perspectives for our understanding of activity on the Sun.

Our observations of the quiescent, or non-flaring, emission from coronal loops are discussed in Section II. It begins with an account of our discovery of the radio wavelength counterpart of coronal loops (Section A). Previous studies of the coronal loops were limited to expensive X-ray telescopes lofted above the Earth's atmosphere in rockets or satellites; but as the result of our discovery, coronal loops can now be observed from the ground using the VLA at 20-cm wavelength. The three-dimensional structure of solar active regions has been specified by multiple-wavelength VLA observations (Section B), where longer wavelengths refer to higher levels within coronal loops. Here we attribute the quiescent radio emission to the thermal radiation of hot electrons trapped within the strong magnetic fields of coronal loops. The microwave brightness

temperature is on the order of the million-degree electron temperature, and either thermal bremsstrahlung or thermal gyroresonant radiation dominate the emission. Bremsstrahlung, or braking radiation, is emitted when the thermal electrons are accelerated in the electric fields of ions, and gyroresonant radiation is emitted when the thermal electrons are accelerated by magnetic fields. Thermal gyroradiation at coronal levels above sunspots has been confirmed by the detection of circularly polarized ring-shaped, or horseshoe, structures at 6-cm wavelength.

One of the key aspects of the VLA observations is that they measure the strength and structure of the coronal magnetic field; this is not possible using any other technique either from the ground or space. The discovery of thermal cyclotron lines in coronal loops (Section C) provides a sensitive new method of specifying the magnetic field strength. Such lines can only be observed with the VLA whose large size permits the resolution of regions with nearly constant magnetic field.

In Section D we present high-resolution comparisons of ground-based VLA (at 20 cm) and SMM satellite (X-rays) observations of coronal loops. The X-ray emission from coronal loops (SMM) is completely imaged at 20 centimeters wavelength (VLA); but there is also 20 cm emission in regions where there is no detectable X-ray radiation. Spectral lines detected at X-ray wavelengths with the SMM were used to infer the electron temperature, emission measure and electron density, while the VLA data were used to determine brightness temperature, optical depth and magnetic field strength. Comparisons of the two sets of data (SMM and VLA) indicate that systems of coronal loops within a single active region have different temperatures and different radiation mechanisms that can only be detected by observations in both the X-ray and radio regions of the electromagnetic spectrum.

VLA observations of large-scale magnetic loops at 90-cm wavelength are discussed in Section E. Enhanced 90-cm emission is associated with elongated loop-like structures that are associated with filaments and coronal streamers; depressions in the 90-cm radiation are associated with coronal holes. This new VLA system therefore has a lot of future potential for studies of solar activity.

Our VLA studies of radio bursts from coronal loops are discussed in Section III. It begins with snapshot maps, made at intervals of up to 3 seconds, that reveal mechanisms for triggering solar eruptions (Section F). It is magnetic interaction of the invisible coronal loops, and temperature enhancements within these loops, that play the dominant role in the excitation of solar bursts. Preexisting or newly-emerging coronal loops may interact; when oppositely polarized sections of bipolar loops meet, they can reconnect and trigger an explosion in the process. Explosive instabilities can also occur when the coronal plasma is heated beyond the confining limits of the magnetic field. Magnetic triggering and pre-explosive heating in coronal loops precede solar eruptions on time scales of 10 to 15 minutes.

The VLA has also demonstrated that radio energy release occurs at the apex of coronal loops, while the optical flares occur at their foot points (Section G). Since the radio radiation is emitted by high-speed, energetic electrons, it delineates the region of particle acceleration. The magnetic interaction of coronal loops apparently involves reconnection processes that release stored energy and accelerate particles near their tops.

Our VLA observations at the relatively short wavelength of 2 centimeters (Section H) have led to the discovery of compact (angular sizes $9'' - 10''$), transient (seconds to minutes) sources. The highly-polarized emission may be due to new magnetic dipoles that emerge in the transition region and expand outwards into the corona. The rising magnetic loops could act as small, erupting coronal loops, thereby providing a source of energy for heating the corona.

New technological developments at the Very Large Array (VLA) have recently made it possible to observe the inner solar corona at 92 centimeters wavelength with an unprecedented angular resolution of 5 seconds of arc. This is an improvement of almost two orders of magnitude over all previous telescopes operating at this wavelength. It has enabled us to resolve noise storms, the most frequent type of solar radio activity, for the first time (Section I). Individual noise storm bursts and the background continuum have been resolved in both space and time by using simultaneous observations with the VLA and the Nancay Radioheliograph. Such information will provide important constraints to our future understanding of noise storms and related activity on the Sun.

VLA observations of radio bursts from nearby stars are discussed in Section IV. It begins with our discovery of very rapid, millisecond variations in the radio emission of flare stars (Section J); such variations provide severe limits to the source size, $L < 10^8$ cm or less than 0.005 of a stellar radius, and brightness temperatures, $T_b > 10^{16}$ °K, that require coherent radiation mechanisms. Such mechanisms have been confirmed by the detection of narrow-band structure that cannot be produced by any known incoherent process - either thermal or nonthermal (Section K). The coherent radiation mechanisms (Section L) suggest physical conditions in stellar coronae that are comparable to those in the Sun's corona, with an electron density of $N_e = 6 \times 10^9$ cm⁻³ and a magnetic field strength of $H = 200$ Gauss. This suggests that we carefully examine solar bursts for signatures of coherent radiation mechanisms; at least one example has, in fact, been detected during our VLA observations of explosive radio outbursts from solar active regions.

Section V lists the titles and journal references for the thirty-eight (38) papers that were published in 1983 to 1988; they all acknowledge support from grant AFOSR-83-0019. Reprints of these papers are given in Section X - an appendix that has been sent under separate cover. The twenty five (25) presentations at professional meetings and workshops during 1983 to 1988 are described in Section VI .

Support from grant AFOSR-83-0019 has led to the development of reliable, systematic solar observations with the Very Large Array. Our requests to use this multi-million dollar facility have never been rejected. Altogether we carried out twenty-eight (28) observing sessions at the Very Large Array between 1983 and 1988; the proposed abstracts for these observations are given in Section VII.

The facilities used to carry out this research are described in Section VIII; they include the Very Large Array; the SMM satellite and the Nancay Radioheliograph. By combining simultaneous observations of the Sun with all three instruments, we have enhanced the scientific return beyond that expected from using any one of them alone. The costs of operating these expensive facilities have been met by other agencies, including the NSF and NASA. Grant AFOSR-83-0019 has mainly provided salary support and travel expenses for two scientists who have obtained, analyzed and published the relevant data. It has been a very cost effective way of obtaining information about solar activity with the world's most powerful instruments.

The relevance of the accomplished research to the AFOSR is discussed in Section IX. By examining the ubiquitous coronal loops, we have gained new insights to the way in which explosions erupt from them. These explosive bursts create and expel energetic particles and radiation that perturb the aerospace environment and disrupt or interfere with satellites or high-flying aircraft.

II. QUIESCENT EMISSION FROM CORONAL LOOPS

The radio emission from quiescent, or non-flaring, active regions has an intensity that is correlated with sunspot number and area. It arises at all levels within the solar atmosphere above active regions, from the chromosphere to the corona. Because this quiescent emission varies slowly over time scales of several hours, one may investigate its detailed structure by using the Earth-rotation aperture synthesis technique. When the Very Large Array, or VLA, is used in this way, the rotation of the Earth changes the relative orientation of the array and the radio source; Fourier inversion methods are then used to determine the angular power distribution of the radio source from the array response (visibility functions). Angular resolutions of better than one second of arc are achieved for fields of view that can be as large as the entire solar disc. These angular resolutions exceed those of optical telescopes or existing spacecraft telescopes at X-ray or ultraviolet wavelengths.

Synthesis maps of total intensity, I , describe the two-dimensional distribution of source brightness temperature, whereas synthesis maps of circular polarization, or Stokes parameter V , describe the two-dimensional structure of the magnetic field. When applied to solar active regions, the VLA synthesis maps have resulted in several significant and unexpected results including: the discovery of the radio wavelength counterpart of coronal loops (Section A), the specification of the three-dimensional structure of solar active regions (Section B), the discovery of thermal cyclotron lines (Section C), a detailed, high-resolution comparison with simultaneous X-ray observations (Section D), and the discovery of large-scale magnetic loops that can connect active regions with more distant regions on the solar surface (Section E).

A. Discovery of the Radio Wavelength Counterpart of Coronal Loops (at 20 cm Wavelength).

The high spatial and spectral resolution of the X-ray instruments aboard the Skylab and Solar Maximum Mission (SMM) satellites showed that coronal loops dominate the structure of the low solar corona. The magnetic loops trap the hot, million-degree plasma that radiates at X-ray wavelengths. Coronal loops within individual active regions store magnetic energy and suddenly release it during powerful eruptions.

Previous studies of coronal loops were limited to expensive X-ray telescopes lofted above the Earth's atmosphere. But as the result of our discovery, coronal loops can now be observed from the ground with the Very Large Array (VLA) at 20-cm wavelength (see Figure 1).

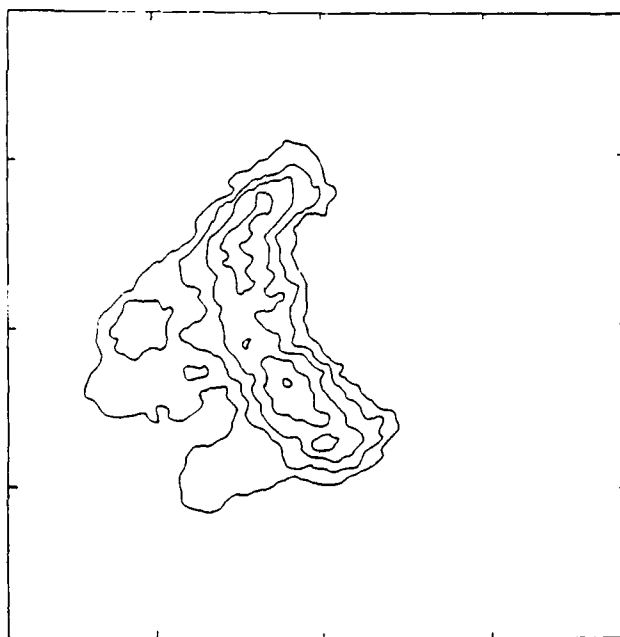


Fig. 1. A typical radio wavelength (20 cm) V.L.A. map of the hot, million-degree plasma trapped in a coronal loop. The angular scale between fiducial marks on the axes is 60 arc-seconds.

The microwave synthesis maps of circular polarization uniquely provide direct measurements of the strength and structure of the magnetic fields in the low corona. When thermal bremsstrahlung is the dominant radiation mechanism, the circular polarization is due to propagation effects in the presence of a magnetic field; the longitudinal magnetic field strength is then inferred from the polarization and the optical depth. When gyroresonant radiation of thermal electrons dominates, the circularly polarized radiation is emitted at the second or third harmonic of the gyrofrequency. One is then able to infer the coronal magnetic field strength from the observed frequency. This is not possible using any other technique with any other instrument, either from the ground or from space.

The detailed temperature and magnetic structure of the quiescent, or non-flaring, coronal loops has therefore been specified using VLA synthesis maps at 20-cm wavelength. These maps describe the two-dimensional distribution of source brightness and the two-dimensional strength and structure of the magnetic field. The unique ability to specify the strength and structure of the coronal magnetic fields is an important aspect of our discovery of the radio wavelength counterpart of coronal loops.

B. Three-Dimensional Structure of Solar Active Regions

Observations at different radio wavelengths generally sample different levels within coronal loops, with longer wavelengths referring to higher levels. This is because the local electron density, N_e , decreases with height, and emission at a given frequency, ν , can arise only from regions where the electron plasma frequency, $\nu_p = 8.9 \times 10^3 N_e^{1/2}$ Hz is equal to or lower than ν . The heights of the radio structures can be inferred from their angular displacements from underlying photospheric features, and the two-dimensional maps at different radio wavelengths can be combined to specify the three-dimensional structure of coronal loops.

We have used multiple-wavelength VLA observations to delineate the temperature and magnetic structure at different heights in coronal loops, thereby providing the first three-dimensional specification of their structure. At each wavelength, the synthesis maps of total intensity, I , describe the two-dimensional distribution of brightness temperature, while the synthesis maps of circular polarization, or Stokes parameter V , describe the two-dimensional structure of the magnetic field. The two-dimensional maps at different wavelengths were then combined to specify the three-dimensional structure of solar active regions (see Figure 2).

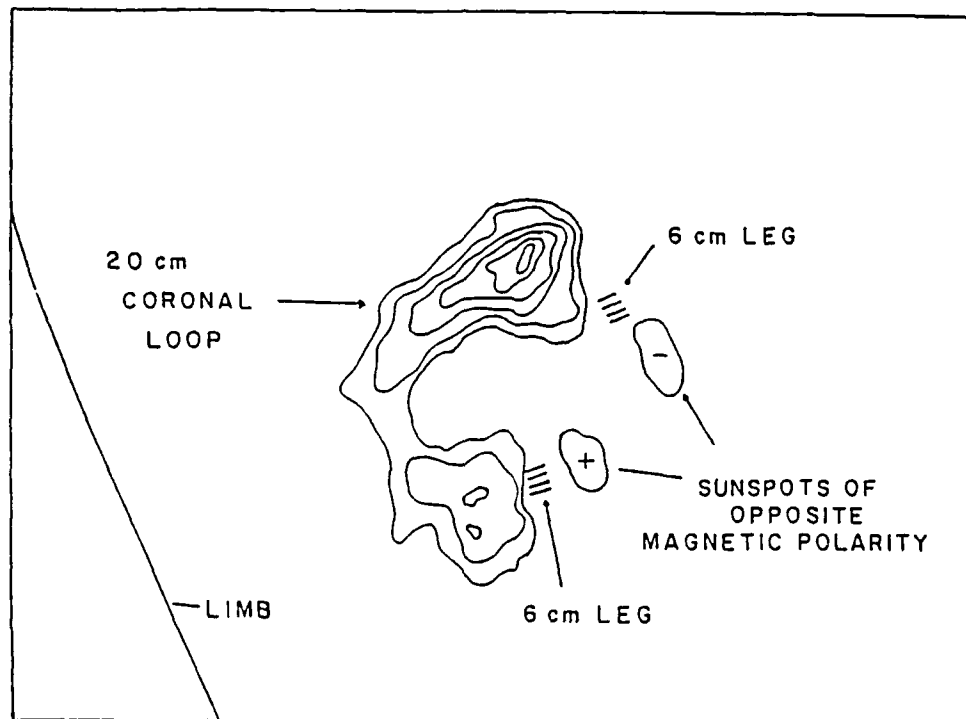


Fig. 2. A VLA synthesis map of the total intensity, I , of the 20 cm emission from a coronal loop. The contours mark levels of equal brightness temperature corresponding to 0.2, 0.4, ...1.0 times the maximum brightness temperature of $T_B = 2 \times 10^6$ OK. A schematic portrayal of the 6 cm emission, which comes from the legs of the magnetic loops, has been added together with the underlying sunspots that are detected at optical wavelengths.

The quiescent component of solar radio emission is thermal in nature, with brightness temperatures that do not normally exceed the local electron temperatures. In fact, the near equality of the radio brightness and electron temperatures indicates that the quiescent radio emission from coronal loops is usually thermal. At centimeter wavelengths there are two different thermal mechanisms: the bremsstrahlung of thermal electrons accelerated in the electric field of ions and the gyroresonant radiation of thermal electrons accelerated by magnetic fields. While the thermal bremsstrahlung emission is sensitive to the electron temperature and emission measure, gyroresonant emission is sensitive to the local magnetic field and electron temperature. It is this gyroresonant radiation which provides a sensitive measure of the coronal magnetic field strength. Thus, it is important to distinguish which of these mechanisms is responsible for the emission from any given source at these wavelengths.

The most intense emission from solar active regions at 6 cm wavelength originates in the legs of magnetic dipoles that have their foot points in underlying sunspots. Coronal temperatures are inferred from the high brightness temperatures of $T_B \sim 10^6$ K, whereas heights $h \sim 40,000$ km are inferred from angular displacements from the underlying sunspots. The low electron density above sunspots requires gyroresonance absorption if the bright 6 cm emission is to be explained.

Gyroresonant emission in the legs of magnetic dipoles at 6 cm wavelength has been confirmed by our discovery of circularly polarized horseshoe or ring shaped structures that lie above the curved magnetic fields of sunspot penumbrae. (see Figure 3). The high degrees of circular polarization $\rho_c \sim 95\%$ of these horseshoes requires gyroresonant emission, and the structures were, in fact, predicted from the theory of gyroresonant emission of individual sunspots.

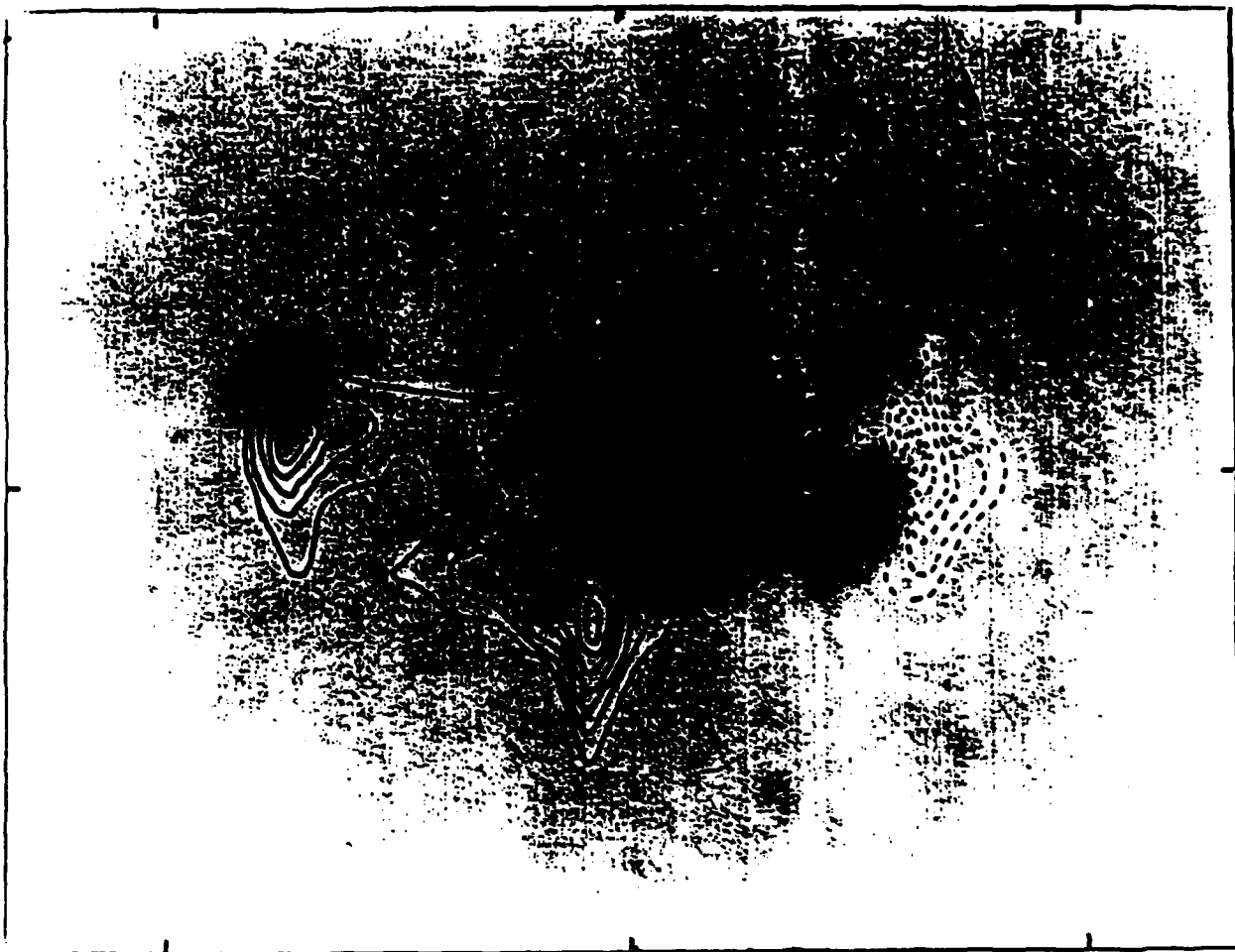


Fig. 3. A VLA synthesis map of circular polarization showing a circularly polarized horseshoe structure. It is superposed on an off-band $H\alpha$ photograph of the same region taken on the same day. The angular scale is denoted by the $60''$ spacing between the fiducial marks on the axes. Notice that there is no detectable polarized emission above the sunspot umbrae where the magnetic fields are strong and nearly vertical, and that the polarized emission is concentrated above the penumbrae, where the magnetic field lines are curved and the field strength is weaker and has a sharp gradient.

Much, if not all, of the 20-cm emission is due the thermal bremsstrahlung of the same hot plasma that gives rise to the soft X-ray emission. Because the magnetic energy density dominates the thermal energy density in the low solar corona, this plasma usually remains trapped within the magnetic loops. The 20-cm brightness temperatures are then on the order of the million-degree electron temperature.

We have completed multiple-wavelength synthesis maps using the VLA at wavelengths $\lambda = 20, 6$ and 2 cm. The radiation at 20 cm originates at both the apex and legs of coronal loops, and usually delineates the hot, dense plasma detected at X-ray wavelengths. Electron temperatures of $T_e = 2$ to 4×10^6 K, electron densities of $N_e = 10^9$ to 10^{10} cm $^{-3}$ and loop extents $L = 10^9$ to 10^{10} cm are inferred from the 20 cm radiation. Magnetic field strengths of $H \sim 145$ G have been inferred from cyclotron lines at the apex of some 20 -cm loops (see the next Section C). Bright, highly polarized 6 -cm cores often mark the legs of dipolar loops with $T_B = 2 \times 10^6$ to 5×10^6 K and heights $h \sim 10^9$ cm above the underlying sunspots. Values of H of ~ 600 to 900 G are inferred from the fact that these cores emit gyro radiation at the second or third harmonic of the gyrofrequency. The 2 -cm emission has brightness temperatures of $T_B \sim 10^5$ K and often overlies sunspots at heights $h \sim 5 \times 10^8$ cm where H is $\sim 10^3$ G.

C. Discovery of Thermal Cyclotron Lines in Coronal Loops.

The microwave radiation of coronal loops is often dominated by the gyroemission of energetic electrons. The thermal electrons gyrate around the magnetic fields, emitting cyclotron lines at harmonics of the gyrofrequency. The frequency, ν , of the cyclotron lines therefore provides a sensitive measurement of the longitudinal magnetic field strength, H , through the relation $\nu = 2.8 \times 10^6$ nH Hz, where the harmonic number $n = 2, 3, 4, \dots$. However, because the magnetic field strength in a coronal loop decreases uniformly with height, it was thought that the individual cyclotron lines would merge to form a smooth continuum.

Theoretical speculations have nevertheless led to two hypothetical situations in which individual cyclotron lines might be observed. The presence of neutral current sheets might lead to enhanced emission from relatively thin coronal layers where the magnetic field is constant. The individual cyclotron lines might then be detected if the region of current sheet emission was resolved and appropriate spectral data were obtained near the loop apex. Alternatively, the thermal cyclotron emission from the legs of a dipolar loop might be detected through

spatial and polarization structures that are sensitive to both observation frequency and the angle of observation.

When the magnetic field strength is relatively constant, the gyroemission occurs at specific wavelengths (harmonics of the gyrofrequency), and observations of these wavelengths (spectral lines) can be used to infer the magnetic field strength. We have observed these spectral features, called thermal cyclotron lines, when the apex of a coronal loop is resolved with the VLA (see Figure 4). These observations provide a unique method of studying the coronal magnetic field, as well as neutral current sheets that may create intense radio emission from a thin layer near the loop apex.

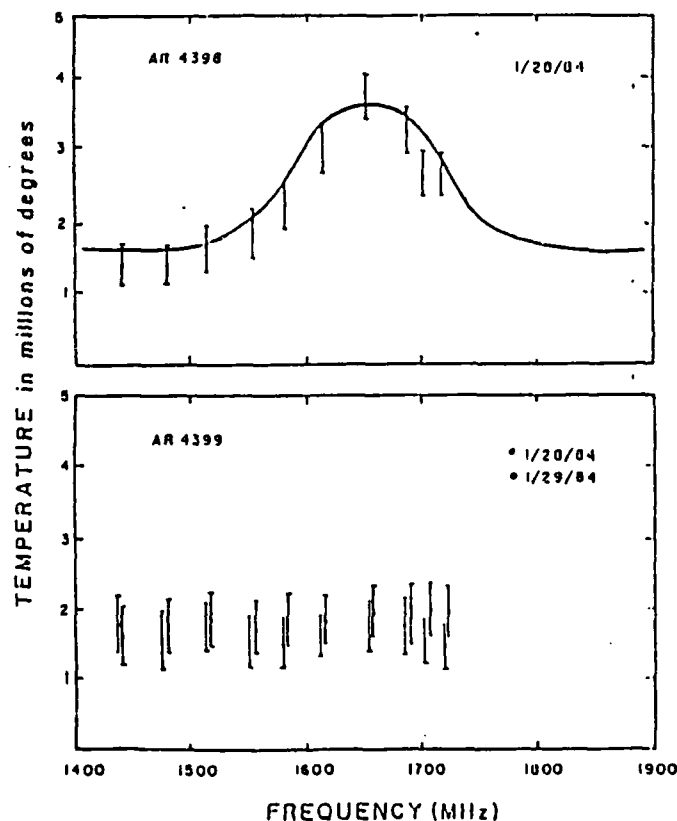


Fig. 4. At 20 centimeters wavelength we have observed the apex of coronal loops where the magnetic field is nearly constant and the spectrum of individual cyclotron lines can be resolved. This will be particularly true if currents or some other process confine the intense emission to a thin, hot layer within the loop apex. The VLA data at ten closely-spaced frequencies near 1446 MHz(20cm), showing thermal cyclotron line spectra from active region AR 4398 on successive days, are placed together with optically-thick thermal bremsstrahlung spectra from active region AR 4399 on the same days.

The discovery of individual cyclotron lines provides a sensitive new diagnostic tool for specifying the magnetic and plasma properties of coronal loops. For example, a change in the magnetic field strength of only 20 Gauss produces a 170 MHz shift in the central frequency of a cyclotron line near 1420 MHz (or 21 cm wavelength). Measurements of the central frequency therefore specify the magnetic field strength with unprecedented precision.

The Very Large Array is the only instrument that is capable of resolving individual coronal loops at microwave wavelengths. It is therefore the only instrument that can observe cyclotron lines. Antennae with poorer angular resolution would observe a continuum caused by the superposition of different cyclotron lines emitted from different coronal loops and varying levels in the solar atmosphere.

D. High-Resolution Comparisons of Ground-Based VLA (at 20 cm) and SMM Satellite (X-rays) Observations of Coronal Loops.

The Principal Investigator of grant AFOSR-83-0019 was also Guest Investigator on the Solar Maximum Mission (SMM) satellite in 1986, 1987 and 1988. This enabled him to arrange simultaneous observations of solar active regions with the SMM X-ray telescope (XRP) and the VLA. The electron density, N_e , and electron temperature, T_e , were inferred from X-ray spectral lines such as O VIII, NE XI, Mg XI, Si XIII, S XV and Fe XXV. These data were compared with simultaneous 20 cm VLA observations of similar field of view and angular resolution, thereby permitting us to specify the radiation mechanisms. Of course, the VLA data also uniquely provide information on the strength and structure of the coronal magnetic fields.

Such comparisons have shown that the structure and dominant radiation mechanisms in the low corona are much more complex and inhomogeneous than was previously thought. As illustrated in figure 5, there are areas where the X-ray coronal loops have been completely imaged at 20-cm wavelength. In other areas,

the X-ray radiation was observed without detectable 20 cm radiation, and vice versa. Thus, systems of coronal loops within a single active region have different temperatures and different radiation mechanisms that can only be detected by simultaneously observing at both X-ray and 20-cm wavelengths. Observations in both spectral regions are required to fully specify the complex coronal structure of solar active regions.

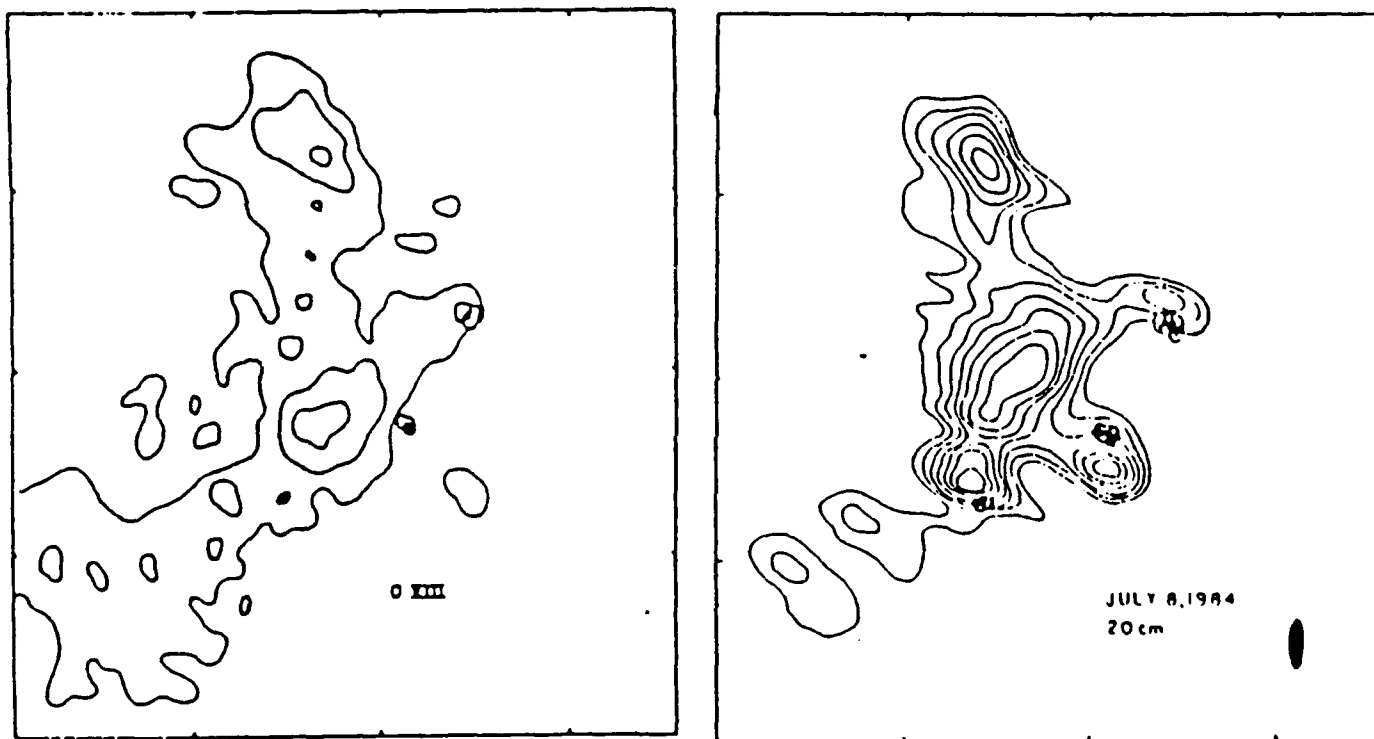


Fig. 5. A comparison of soft X-ray (Solar Maximum Mission Satellite-left) and 20 cm (Very Large Array - right) images of a solar active region. The field of view of both two images is the same, and the angular scale can be inferred from the 120" spacing between the fiducial marks on the axes. The coronal loops join underlying sunspots denoted by the black spots. The hot, dense coronal plasma detected at X-ray wavelengths is fully imaged by the VLA at 20-cm wavelength. The VLA data also show a hot million-degree plasma above sunspots that is not detected with X-ray telescopes.

In some instances, there is radiation at 20 centimeters wavelength near sunspots where no X-ray radiation is detected. The radio emission may be attributed to gyroresonant radiation of a low density plasma in magnetic fields of strength $H = 145$ to 290 G (harmonic $n = 4$ to 2). The near equality of the microwave brightness and electron temperatures indicates that the 20-cm emission is thermal, but the absence of detectable X-ray radiation above sunspots indicates a relatively low electron density there. This means that the high microwave brightness temperature above sunspots can not be due to bremsstrahlung, but it is explained by thermal gyroresonant radiation at the second or third harmonic of the gyrofrequency.

In other cases, the 20 centimeter radiation appears at the apex of coronal loops, but with a slightly lower brightness temperature than the electron temperature inferred from the X-ray data. This may be explained by a low-temperature plasma that lowers the effective brightness temperature of the radio bremsstrahlung while not affecting the X-ray data. Because the line of sight through the low temperature plasma is greatest along the legs of coronal loops, it can reduce the size of the radio source below that of the X-ray emission. That is, the low temperature plasma can, under the right circumstances, confine the detectable radio radiation to the apex of coronal loops.

Thus, when the SMM and VLA data are combined we find evidence for a relatively cool (10^5 K) external plasma that is not detected at X-rays. This external plasma acts as a sheath around the hotter (10^6 K) coronal loops. Both the cool and hot radiation of coronal loops is probably thermal bremsstrahlung; but thermal gyroresonance radiation must account for the intense 20-cm emission near and above sunspots where no X-ray radiation is detected.

E. Large-Scale Magnetic Loops Observed at 90-cm Wavelength

Intense, quiescent radiation at 90-cm wavelength is associated with large-scale magnetic structures. Many of these elongated structures have no optical counterpart including active regions, sunspots or magnetic neutral lines; but

other 90-cm structures are associated with filaments or coronal streamers (see Figure 6). Reductions or depressions in the 90-cm radiation are associated with coronal holes in both the polar and equatorial regions. The high-speed solar wind apparently originates in these coronal holes. Thus, preliminary VLA observations with the new 90-cm system have revealed open and closed magnetic structures that will be the subject of close scrutiny during the coming maximum in solar activity.

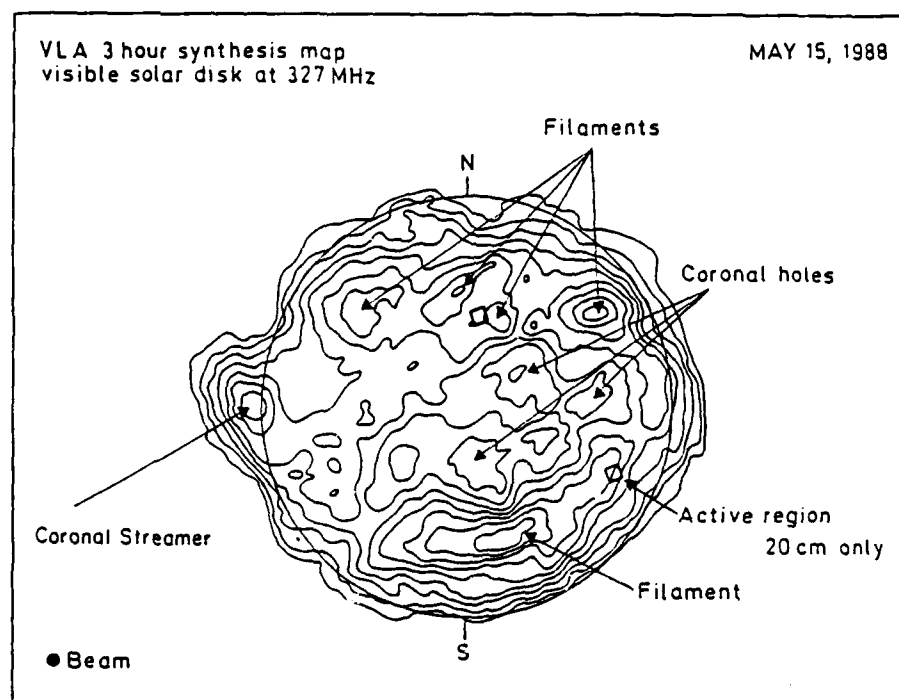


Fig. 6. Three-hour VLA synthesis map at 92-cm wavelength (327.0 MHz) on 15 May, 1988. The regions of enhanced 92-cm emission are well correlated with dark filaments shown in a H α photograph taken on the same day. The elongated filaments have similar shapes at 92-cm and H α wavelengths. Active regions (squares) are not associated with enhanced 92-cm radiation; but they dominate the intense radiation at 20-cm wavelength and are observed as bright H α features. Regions of depressed 92-cm emission are at least partly due to equatorial coronal loops.

III. RADIO BURSTS FROM CORONAL LOOPS

The 27 antennae of the Very Large Array are interconnected electronically to provide a total of 356 interferometer pairs. Signals recorded every three seconds of time therefore provide sufficient data to construct snapshot synthesis maps with angular resolutions of a few seconds of arc without relying on the Earth's rotation to provide variable interferometric baselines. Snapshot maps of total intensity, I , and circular polarization, or Stokes parameter V , can be made at time intervals as short as three seconds. These maps can be used to detect changes in the configuration of coronal magnetic fields and temperature enhancements within coronal loops that are important triggering agents for solar bursts.

The origin and prediction of these powerful bursts is one of the most important and interesting problems of solar physics. It has long been known that solar eruptions are intimately connected with the magnetic fields in active regions, for the ultimate source of energy for these bursts must be magnetic energy. It has only recently been realized, however, that evolving magnetic fields in the solar corona may play a dominant role in triggering solar eruptions.

Our VLA observations indicate that preburst heating within coronal loops and/or the magnetic interaction of coronal loops can trigger solar eruptions (Section F). The explosive energy is released near the apex of coronal loops in regions observed by the VLA (Section G). Bright small-scale loops may be continually erupting, thereby heating the solar corona (Section H); while large-scale coronal loops, that connect active regions with more distant areas on the Sun, are the site of noise storm activity (Section I).

F. Triggering Solar Eruptions

Interferometric observations at microwave wavelengths first indicated that preburst activity is associated with brightness and polarization changes

that precede solar bursts on time scales of tens of minutes; but these observations had inadequate resolution to determine the sources of this activity. The high angular resolution provided by the Very Large Array has shown that the intensity or brightness increases are associated with preburst heating in coronal loops, and that the changes in circular polarization are associated with changes in the coronal magnetic field. Both the preburst heating in coronal loops and the changes in coronal magnetic fields may trigger solar eruptions.

As illustrated in Figure 7, single coronal loops or arcades of loops often begin to heat up and change structure about 15 minutes before the eruption of impulsive bursts. Radio and soft X-ray data have been combined for this example to derive a peak electron temperature of $T_e = 2.5 \times 10^7$ K and an average electron density of $N_e = 10^{10} \text{ cm}^{-3}$ during the heating phase. The heating apparently develops an unstable situation, leading to the release of high-energy particles in solar bursts or eruptions.

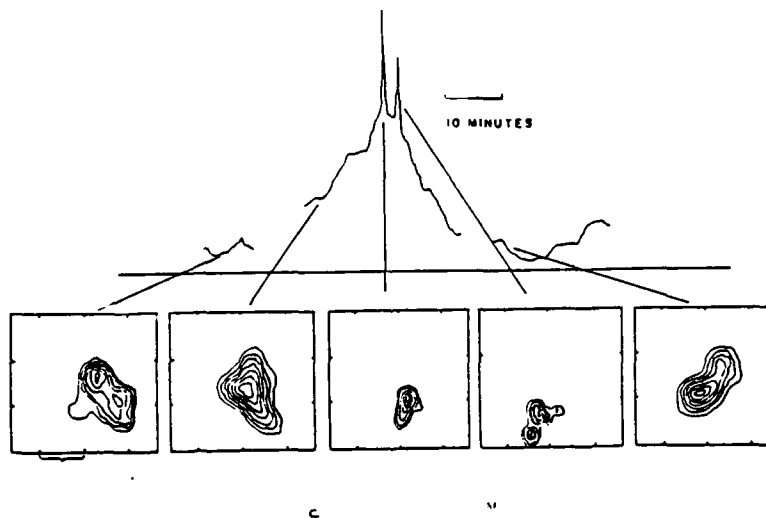


Fig. 7. The time profile of a solar burst at $\lambda = 20\text{cm}$ (top of figure), suggests heating within a coronal loop prior to the emission of two impulsive microwave bursts. The 20 cm VLA synthesis maps for 10-second intervals (bottom of figure) suggest that a coronal loop twisted in space.

Theoretical considerations indicate that loops emerging into the corona, magnetic shear within these loops, and interacting coronal loops can also trigger solar eruptions and supply their energy. Our VLA observations have played a crucial role in demonstrating that many of these theoretical effects actually take place on the Sun. These observations indicate that no single theoretical model is versatile enough to explain the diverse ways in which magnetic energy is dissipated in solar bursts. They nevertheless indicate that preburst changes can be ordered into three major categories - changes within a single coronal loop, the emergence of coronal loops, and interaction between coronal loops.

New bipolar loops can emerge and interact with preexisting ones, thereby triggering solar bursts. When the polarity of the new emerging flux differs from that of the preexisting flux, current sheets are produced that trigger the emission of bursts. A similar process can occur when preexisting adjacent loops undergo magnetic changes and trigger eruptions in nearby coronal loops.

Microwave bursts can be sequentially triggered within magnetically complex regions. As illustrated in Figure 8, successive intense bursts can be emitted from spatially separated coronal loops. Here the total intensity of the 20 cm burst emission is mapped. The polarization data indicate that the spatially separated structures are dipolar loops. In contrast to the intense bursts, the successive weaker bursts shown in the time profile were emitted from the same loop as the immediately preceding intense burst.

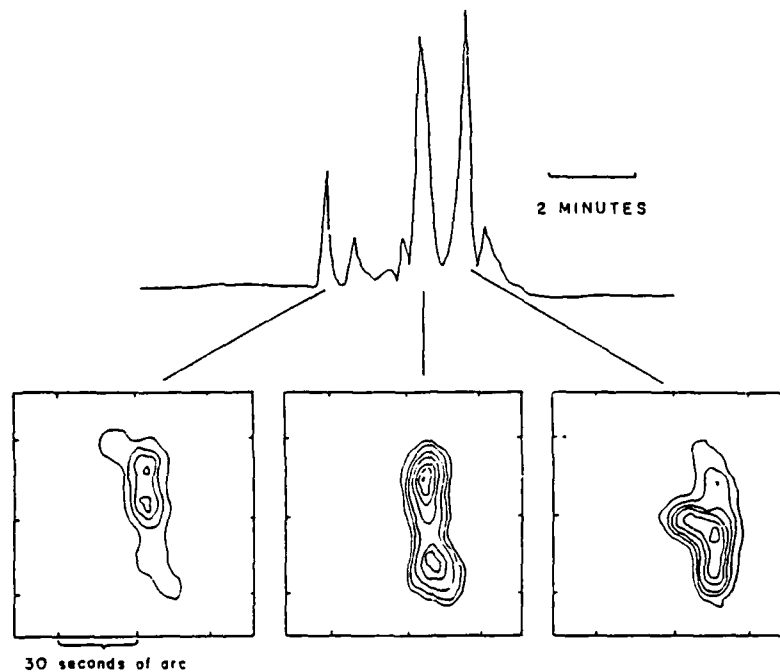


Fig. 8. The time profile of successive impulsive bursts at 20 cm wavelength is compared with ten second V.L.A. synthesis maps at the same wavelength. Here the contour intervals are in steps of 1.0×10^7 K and the angular scale can be inferred from the 30" spacing between fiducial marks on the axes.

G. Site of Energy Release

VLA observations have shown that the site of impulsive energy release is the upper parts of coronal loops rather than the lower-lying levels detected at optical wavelengths (see Figure 9). This means that high-resolution VLA observations must play a key role in examining particle acceleration mechanisms. A nonthermal tail of electrons with energies greater than 100 KeV is created near the top of the coronal loop. Some of these electrons are trapped in the upper parts of the loop, producing the impulsive microwave bursts by synchrotron radiation. Other electrons stream down to the loop footpoints, producing hard X-ray bursts and the H α kernels.

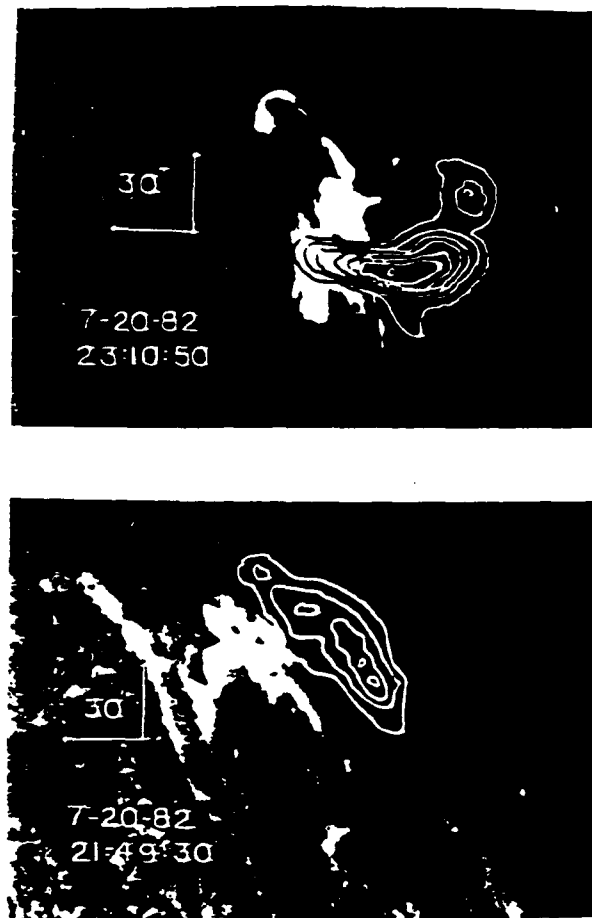


Fig. 9. The ten second VLA synthesis maps of the impulsive phase of two solar bursts at 20 cm wavelength superimposed on H α photographs of the optical flares taken at the same time. The 20 cm bursts originate near the tops of coronal loops that are about 40,000 km above the flaring region seen at optical wavelengths. The western solar limb is visible in both photographs.

H. Compact Variable Sources

Long-wavelength VLA observations (20 cm and 90 cm) sample coronal loops that remain stable for hours and days, but they then suddenly erupt explosively. In contrast, short 2-cm wavelengths delineate compact, rapidly varying sources that may play a role in heating the solar corona. The small (a few seconds of arc), highly circularly polarized (up to 100%) emission varies on time scales of less than 30 seconds to several hours (see Figure 10).

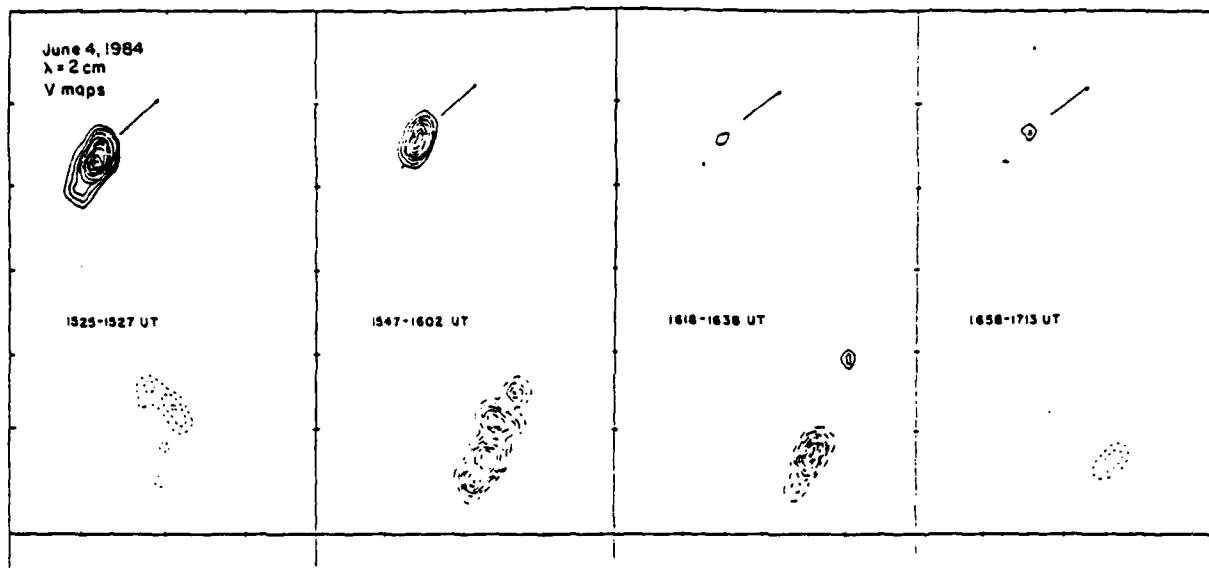


Fig 10. VLA synthesis maps of left circularly polarized (solid contours) and right circularly polarized (dashed contours) radiation at 2 cm wavelength. Here each box refers to the same area on the surface of the Sun, and the fiducial marks on the axes are separated by 10". The northern source (top) varied over time scales of 30 minutes and moved laterally across the solar surface in the northwest direction with a velocity of 1 km s^{-1} . The southernmost source varied over a timescale of about 60 minutes, and moved laterally towards the southwest at a velocity of 2 km s^{-1} .

The rapidly varying, compact 2-cm structures have temperatures, $T_B \approx 10^5 \text{ K}$, sizes, $\theta \approx 10''$, and lifetimes, $\tau \approx 20$ to 80 seconds, that are comparable to rapid brightenings detected at ultraviolet (u-v) wavelengths. These energetic u-v events have been called jets or bullets because of their rapid outward motion; similar lateral motions are detected for the compact, variable 2-cm sources detected with the VLA (also see Figure 10).

Comparisons with Mt. Wilson magnetograms indicate that the compact, variable, moving sources were located in regions of apparently-weak photospheric magnetic field ($H < 80 \text{ G}$), and that they did not overlie sunspots. The high polarization of these sources is therefore very curious, for the polarization of thermal

radiation requires strong magnetic fields of $H \approx 2,000$ G.

The enigmatic presence of highly polarized sources in regions of apparently-weak photospheric magnetic field may be explained by any one of three hypothesis. First, the photospheric field may have strengths of up to 2,000 G in compact regions that are not readily detected by the photospheric magnetograms. Alternatively, the magnetic field in the transition region or the low corona may be amplified by currents to a strength above that in the underlying photosphere. If either of these hypothesis is true, then the high circular polarization of the 2 cm sources can be attributed to either thermal gyroradiation or the propagation of thermal bremsstrahlung in the presence of a magnetic field of strength $H \approx 2,000$ G. A third hypothesis is that the compact 2 cm sources are due to nonthermal gyrosynchrotron radiation of mildly relativistic electrons in relatively weak magnetic fields of strength $H \approx 50$ G, but some as yet unspecified mechanism must be continuously accelerating the electrons.

We have observed at least two of these compact, variable 2-cm sources within the 3' field of view every time we have observed the Sun; extrapolating to the 30' - wide Sun, we would expect hundreds of them on the visible surface of the quiet Sun. The variable sources might therefore play an important role in supplying heat to the corona. One currently unsolved problem in solar physics is how the million-degree corona can remain outside the relatively cool six-thousand-degree photosphere, for heat normally flows from a hot body to a cold one rather than the other way around.

The variability of the compact 2-cm sources might be due to upward-expanding magnetic dipoles whose legs produce the apparent lateral motion of the 2-cm sources. Each expanding dipole might be viewed as a small, erupting coronal loop that feeds magnetic energy into the corona and supplies its previously-unknown source of heat.

I. Noise Storms

Noise storms are the most common type of solar activity observed at metric wavelengths. They consist of a slowly-varying, wide-band continuum radiation with superposed short-lived, narrow-band bursts. These bursts have been designated Type I bursts to distinguish them from other types of solar bursts. The background continuum, which is usually observed between 50 and 350 MHz, normally continues for a few hours, while individual bursts have bandwidths between 2 and 10 MHz and durations of 0.1 to 2 seconds.

Both the background continuum, and the bursts are usually strongly circularly polarized (up to 100%), but unpolarized bursts are occasionally observed. The sense of circular polarization is constant throughout the storm; it is attributed to the ordinary mode of plasma radiation in a strong magnetic field.

The recent installation of long wavelength (92 centimeters) receivers at the Very Large Array (VLA) has improved the angular resolution at this wavelength by more than an order of magnitude when compared with all other instruments. As a result, solar noise storms have been resolved for the first time. This could not previously be done at shorter wavelengths because the radiation is absorbed in the overlying solar atmosphere (plasma frequency in the corona) and does not reach the Earth.

As illustrated in Figure 11, a 92-cm noise storm was resolved into four compact sources, each with an angular diameter of 40 seconds of arc. This diameter corresponds to a linear size of 3×10^9 cm and a minimum duration of 0.1 seconds for waves moving at the velocity of light. The observed limit to the duration of noise storm bursts is also 0.1 seconds, indicating that we have resolved the individual burst emitters. They are located high up on large-scale coronal loops that connect solar active regions with more distant regions on the Sun's surface. These magnetic loops span across a large fraction of the visible solar disk. (The radial height of storm sources is

10^{10} centimeters, or about one seventh of the solar radius).

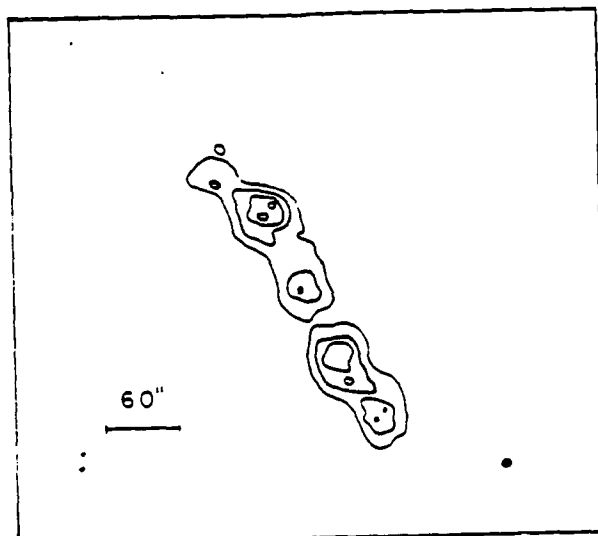


Fig 11. First resolution of a solar noise storm (92 cm wavelength top) into four compact sources about 40 seconds of arc across. This size corresponds to a linear extent of 3×10^9 cm, the distance travelled by radiation moving at the velocity of light for 0.1 seconds. The VLA beamwidth is denoted by the small black dot.

Although the VLA is the only instrument that can spatially resolve many forms of activity on the Sun, it is limited by moderate integration times of $\tau > 3.3$ seconds. We have therefore begun a program of simultaneous observations with the Nancay Radioheliograph (NR) in France whose integration times are $\tau > 0.02$ seconds. Both the VLA and the NR view the entire Sun at the same frequency, 327.0 MHz, and bandwidth, ≈ 700 kHz.

The rapid sampling of the NR instrument permits the isolation of specific types of bursts. Type I bursts during noise storms have, for example, been separated from the background continuum, and the NR data has specified when

the VLA is observing isolated Type I bursts or chains of bursts. The simultaneous French data, which is obtained at no cost to this grant, acts as a time filter, enabling us to specify exactly what the VLA is spatially resolving. We have, for example, shown that unpolarized Type I bursts are emitted by different sources than polarized ones, but that successive polarized Type I bursts are emitted by the same source. Such simultaneous VLA-NR observations will lead to significant results during the coming maximum in the eleven-year cycle of solar activity.

Future simultaneous VLA-NR observations may resolve uncertainties in the driving mechanisms and initiating sources for Type I noise storm bursts, decimeter Type III bursts, and coronal mass ejections. The ejections are, for example, detected by satellite-borne coronagraphs as loop-shaped, magnetically confined plasma that rises and expands outwards into the solar wind. The occulting disks of these coronagraphs block out the inner corona within 1.5 solar radii or more, so these instruments cannot observe the origin of coronal mass ejections. The VLA will, however, be able to observe the regions in the low corona where the ejections originate, and not just at the limb but across the entire visible solar disk.

IV. RADIO BURSTS FROM NEARBY STARS.

The large, unparalleled collecting area of the Very Large Array, VLA, has been used to provide hitherto-unavailable spatial resolution of both quiescent and exploding coronal loops (Sections II and III). Even nearby stars remain unresolved with the VLA, however, and we use its large collecting area to detect the relatively-weak emission from the more-frequent radio bursts of these stars. Studies of explosive phenomena on nearby flare stars have been used to provide new perspectives for our understanding of solar bursts or flares.

Flare stars exhibit a variety of phenomena that are closely related to our understanding of solar active regions including dark spots, strong magnetic fields, activity cycles, and flare emission at optical, ultraviolet, radio and X-ray wavelengths. We have detected rapid variations (Section J) and narrow-band structure (Section K) during radio bursts from these stars, indicating coherent radiation mechanisms that provide constraints on the physical properties of stellar coronae (Section L). Future investigations of radio bursts from the Sun should include searches for the signatures of similar coherent radiation processes.

J. Discovery of Rapid Variations in Stellar Radio Bursts

Observations of the dwarf M flare star AD Leo with high time resolution have provided dramatic evidence for coherent burst emission. As illustrated in Figure 12, a stellar eruption from AD Leo was composed of highly circularly polarized (100 percent) spikes with rise times of less than 5 milliseconds. An upper limit to the linear size of the emitting region is 1.5×10^8 cm, the distance that light travels in 5 milliseconds. If the emitting region is symmetrical, it has an area that is less than 0.005 percent of the star's surface area, and its brightness temperature exceeds 10^{16} K. This is about a billion times hotter than the center of the Sun! Conventional radiation

processes involving normal atomic constituents like electrons would not survive the high temperatures. Positrons would, for example, be produced, annihilating the electrons. So unconventional, coherent radiation processes are required. The high degrees of circular polarization (up to 100%) indicate an intimate connection with the star's magnetic field, and the high brightness temperatures suggest a coherent radiation mechanism such as an electron-cyclotron maser or coherent plasma radiation.

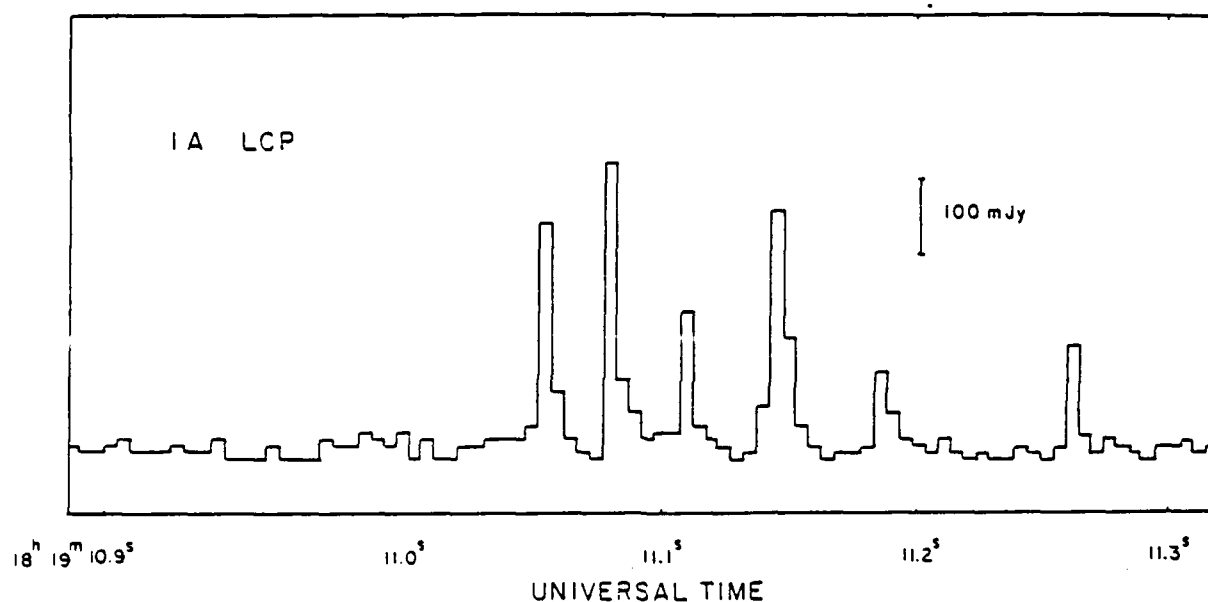


Fig. 12. The total power detected at a frequency of 1415 MHz (21.2 cm) while tracking the dwarf M star AD Leonis. The left-hand circularly polarized (LCP) signal has been displayed with a 5 ms integration time. There are five quasi-periodic spikes with a mean periodicity of $T_p = 32 \pm 5$ ms and a total duration of $\tau_D = 150$ ms. Each of these spikes had a rise time of $\tau_R < 5$ ms, leading to an upper limit to the linear size $L < 1.5 \times 10^8$ cm for the spike emitter. A symmetric source of this size would have a brightness temperature of $T_B > 10^{16}$ K, requiring a coherent radiation mechanism.

K. Discovery of Narrow-Band Structure in Stellar Radio Bursts

At one time, gyroresonance radiation of thermal electrons in extensive coronae was believed to be the most likely explanation for the slowly varying quiescent emission of dwarf M flare stars. Sizes amounting to a few stellar radii were obtained following detection of low flux densities at 6 cm wavelength, and gigantic coronal loops of about three times larger than the visible star were envisaged. However, we have now detected stronger slowly-varying emission at longer wavelengths (20 cm) from YZ Canis Minoris. Inconceivably strong magnetic fields (hundreds of Gauss) extending out to 200 stellar radii are required if gyroresonance emission explains the 20-cm radiation.

Our observations of narrow-band structure in radio bursts from YZ Canis Minoris (see Figure 13) additionally rule out conventional thermal or nonthermal radiation mechanisms. The narrow-band structure cannot be explained by continuum emission processes such as thermal bremsstrahlung, thermal gyroresonant radiation or nonthermal gyrosynchrotron radiation. Although gyroresonant radiation can give rise to narrow-band cyclotron lines, it requires an implausibly large source that is hundreds of times larger than the star. The observations of narrow-band structure can apparently only be explained by coherent mechanisms like electron-cyclotron lines or coherent plasma radiation.

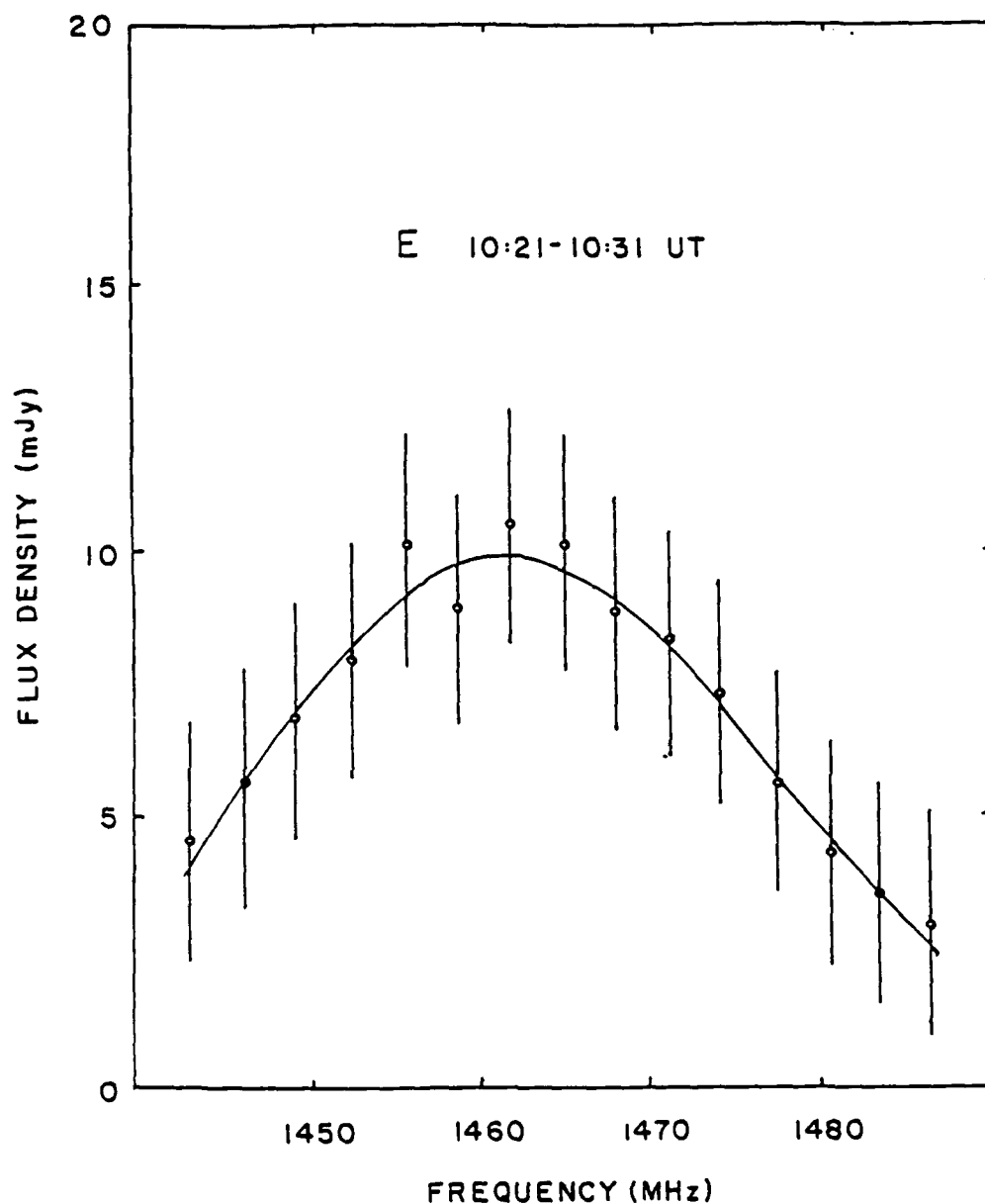


Fig. 13. Frequency spectra of the left circularly polarized radiation from YZ Canis Minoris during one ten-minute radio burst. Here we have plotted the total intensity received in 15 contiguous channels, each 3.125 MHz wide. The vertical error bars denote 3 standard deviations. The narrow-band emission with width $\Delta\nu \approx 30$ MHz can only be explained by a coherent radiation process.

L. Coherent Radiation Mechanisms for Stellar Radio Bursts.

The coherent processes provide constraints on the electron density, N_e , and the magnetic field strength, H , in the stellar coronae. If the radiation is emitted by an electron-cyclotron maser at the second harmonic of the gyrofrequency, then the magnetic field strength is $H = 250$ G, and constraints on the plasma frequency imply an electron density of $N_e \approx 6 \times 10^9 \text{ cm}^{-3}$. Coherent plasma radiation at the first or second harmonic of the plasma frequency respectively require $N_e \approx 2 \times 10^{10} \text{ cm}^{-3}$ and $H \ll 500$ G or $N_e \approx 6 \times 10^9 \text{ cm}^{-3}$ and $H \ll 250$ G. Thus, the coherent burst mechanisms suggest that the coronae of dwarf M stars have physical parameters similar to those of solar active regions.

This suggests that coherent radiation processes might be responsible for some radio bursts on the Sun. Signatures of these processes, such as rapid variations or narrow-band structures, should therefore be investigated during solar eruptions. We have, in fact, observed one example of narrow-band emission (see Figure 14), suggesting that added evidence may be obtained when high time resolution enables the VLA to resolve individual coherent emitters in space, time and frequency.

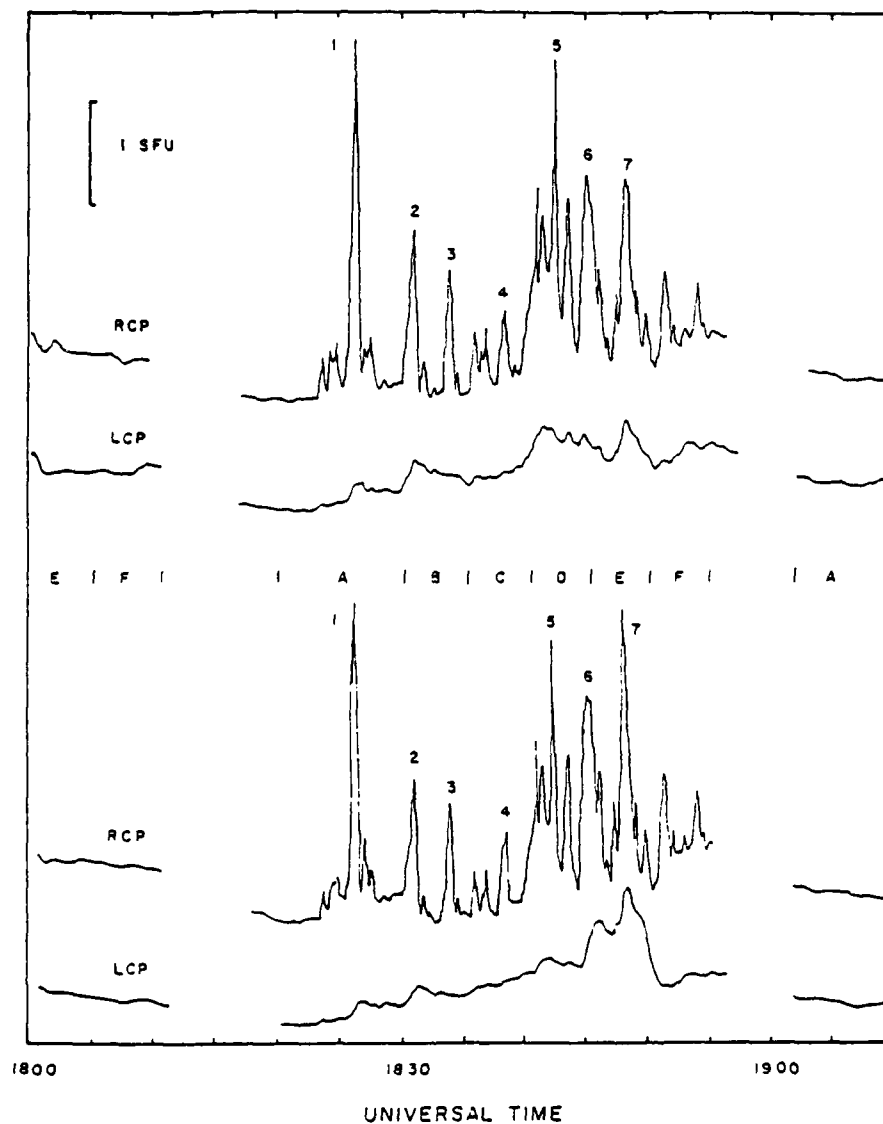


Fig. 14. A sequence of right circularly polarized (RCP) impulsive bursts from a solar active region observed at wavelengths near 20 cm. The top and bottom profiles are separated by only 30 MHz. Burst 7 has a factor of two difference in brightness temperature over this narrow frequency interval; suggesting coherent burst emission.

V. LIST OF PAPERS PUBLISHED 1983 - 1988

1. "Multiple Wavelength Observations of Flaring Active Regions", Kenneth R. Lang and Robert F. Willson, Advances in Space Research, Proceedings of the 24th Plenary Meeting of COSPAR (Committee on Space Research), Volume 2, No. 11, pp. 91-100, Pergamon Press, London 1983.
2. "Very Large Array Observations of Solar Active Regions III. Multiple Wavelength Observations", Kenneth R. Lang, Robert F. Willson and Victor Gaizauskas, Astrophysical Journal 267, 455-464 (1983).
3. "High-Resolution Observations of Solar Radio Bursts at 2, 6 and 20 cm Wavelength, Robert F. Willson, Solar Physics 83, 285-303 (1983).
4. "The Circularly Polarized Sun at 12.6 cm Wavelength", Kenneth R. Lang and Robert F. Willson, Astronomy and Astrophysics 127, 135-139 (1983).
5. "Bright, Rapid, Highly Polarized Radio Spikes from the M Dwarf AD. Leonis", Astrophysical Journal (Letters) 272, L15-L18 (1983).
6. "Possible Detection of Thermal Cyclotron Lines from Small Sources within Solar Active Regions", Robert F. Willson, Solar Physics 89, 103-113 (1983).
7. "Observations of Preburst Heating and Magnetic Field Changes in a 20 cm Loop", Robert F. Willson, Solar Physics, 92 189-198 (1984).
8. "Very Large Array Observations of Solar Active Regions IV. Structure and Evolution of Radio Bursts from 20 cm Loops", Robert F. Willson and Kenneth R. Lang, Astrophysical Journal 279, 427-437 (1984).

9. "The Structure of a Solar Active Region from RATAN-600 and Very Large Array Observations", Kenneth R. Lang, et. al., Astrophysical Journal 301, 460-464 (1985).
10. "The Solar-Stellar Connection", Kenneth R. Lang, Proceedings of the INDO-US Workshop on Solar-Terrestrial Physics, (National Physical laboratory: New Delhi, India, 1986) pp. 21-42.
11. "Short Term Prediction of Solar Bursts - Radio Wavelength Precursors", Kenneth R. Lang, Proceedings of the Solar Terrestrial Prediction Workshop (Observatoire de Paris, Meudon, 1984) pp. 613.
12. "VLA Observations of Flare Build Up in Coronal Loops on the Sun and Solar Type Stars", Kenneth R. Lang and Robert F. Willson, Advances in Space Research, Proceedings of the 25th Plenary Meeting of COSPAR (Committee) on Space Research, Pergamon Press. London, 1984.
13. "The Sun and Nearby Stars: Microwave Observations at High Resolution", Mukul R. Kundu and Kenneth R. Lang, Science 228, 9-15 (1985).
14. "Microwave Observations of Late-Type Stars with the Very Large Array" Roberto Pallavicini, Robert F. Willson and Kenneth R. Lang, Astronomy and Astrophysics 149, 95-101 (1985).
15. "VLA Observations of Narrow-Band Decimetric Burst Emission", Robert F. Willson, Solar Physics 96, 199-207 (1985).
16. "VLA Observations of Solar Active Regions at Closely Spaced Frequencies: Evidence for Thermal Cyclotron Line Emission", Robert F. Willson, Astrophysical Journal 298, 911-917 (1985).

17. "High-Resolution Microwave Observations of the Sun and Nearby Stars", Kenneth R. Lang, Solar Maximum Analysis (ed. V.E. Stepanov and V.N. Obridko, VNU Science Press, 1986) pp. 69-89.
18. "Solar Burst Precursors and Energy Build Up at Microwave Wavelengths", Kenneth R. Lang and Robert Willson, Advances in Space Research 6 no. 6 97-100 (1986).
19. "Radio Wavelength Observations of Magnetic Fields On Active Dwarf M, RS CVN And Magnetic Stars", by Kenneth R. Lang, Advances in Space Research 6, no. 6, 109-112 (1986).
20. "VLA Observations of Compact, Variable Sources on the Sun", Robert F. Willson and Kenneth R. Lang, The Astrophysical Journal 308, 443-447 (1986).
21. "Flare Stars and Solar Bursts: High Resolution In Time and Frequency" Kenneth R. Lang, Solar Physics 104, 227-233 (1986).
22. "Coronal Plasmas On The Sun And Nearby Stars", Kenneth R. Lang, Coronal and Prominence Plasmas, (NASA Conference Pub. 2442, 1986) pp. 309-317.
23. "Compact, Variable Moving Sources Observed On the Sun At 2 Centimeters Wavelength", Kenneth R. Lang and Robert F. Willson, Coronal and Prominence Plasmas, (NASA Conference Pub. 2442 - 1986) pp. 353-357.
24. "Coronal Diagnostics", Kenneth R. Lang, Coronal and Prominence Plasmas NASA Conference Pub. 2442, - U.S. Govt. Printing, 1986) pp. 279-289.

25. "Narrow-Band, Slowly Varying Decimetric Radiation From The Dwarf M Flare Star YZ Canis Minoris, Kenneth R. Lang and Robert F. Willson, The Astrophysical Journal (Letters) 302, L17-L22 (1986).
26. "Millisecond Radio Spikes From the Dwarf M Flare Star AD Leonis", Kenneth R. Lang and Robert F. Willson, The Astrophysical Journal, 305, 363-368 (1986).
27. "Compact, Variable Sources on the Sun at 2 Centimeter Wavelength", Robert F. Willson and Kenneth R. Lang, Solar Physics 114, 93-104 (1987).
28. "Multiple Wavelength Microwave Observations of the RS Canum Venaticorum Stars UX Arietis, HR 1099, HR 5110 and II Pegasi", Robert F. Willson and Kenneth R. Lang, Astrophysical Journal 312, 278-283 (1987).
29. "VLA Observations of a Solar Noise Storm", Kenneth R. Lang and Robert F. Willson, The Astrophysical Journal 319, 514-519 (1987).
30. "Simultaneous SMM Flat Crystal Spectrometer And Very Large Array Observations Of Solar Active Regions", Kenneth R. Lang, Robert F. Willson, Kermit L. Smith, and Keith T. Strong, The Astrophysical Journal 322, 1035-1043 (1987).
31. "Solar Active Region Physical Parameters Inferred From A Thermal Cyclotron Line and Soft X-ray Spectral Lines", Kenneth R. Lang, Robert F. Willson, Kermit L. Smith, and Keith T. Strong, The Astrophysical Journal 322, 1044-1051 (1987).
32. "Ultraviolet And Radio Flares From UX Arietis And HR 1099", Kenneth R. Lang and Robert Willson, Astrophysical Journal 328, 610-616 (1988).

33. "VLA Observations Of Dwarf M Flare Stars And Magnetic Stars", Robert F. Willson, Kenneth R. Lang and Prudence Foster, Astronomy and Astrophysics 199, 255-261 (1988).
34. "High Resolution VLA Maps of The Quiescent Corona At 90 cm Wavelength" Kenneth R. Lang, Robert F. Willson and Gerard Trottet, Astronomy and Astrophysics 199, 325-328 (1988).
35. "Narrow-Band, Slowly Varying Decimetric Radiation From the Dwarf M Flare Star YZ Canis Minoris II", Kenneth R. Lang and Robert F. Willson, Astrophysical Journal 326, 300-304 (1988).
36. "Microwave Observations of Solar and Stellar Coronae", Robert F. Willson in Solar and Stellar Coronal Structure and Dynamics (ed. Richard C. Altrock, National Solar Observatory, 1988) pp. 54-65.
37. "Simultaneous VLA-Satellite Observations of the Sun", Kenneth R. Lang. Advances in Space Research, Proceedings of the XXVII Committee on Space Research (COSPAR) Meeting (Pergamon Press, 1988).
38. "High-Resolution VLA-Nancay Observations of the Sun", Alain Kerdraon, Gerard Trottet, Kenneth R. Lang and Robert F. Willson, Advances in Space Research; Proceedings of the XXVII Committee on Space Research (COSPAR) Meeting (Pergamon Press, 1988).

VI. PAPERS PRESENTED AT PROFESSIONAL MEETINGS AND WORKSHOPS 1983-1988.

1. "VLA Observations of Quiescent Active Regions", Kenneth R. Lang, 161st Meeting of the American Astronomical Society, Boston, January 9-11, 1983.
2. "VLA Observations of Solar Bursts", Robert F. Willson, 161st Meeting of the American Astronomical Society, Boston, January 9-12, 1983.
3. "Multiple Wavelength Observations of Solar Active Regions", Kenneth R. Lang, Second Solar Maximum Mission Workshop, Goddard Space Flight Center, June 9-14, 1983.
4. "Preflare Heating and Magnetic Precursors of Solar Bursts:", Robert F. Willson, Big Bear Solar Observatory, June 16-20, 1983.
5. "Very Large Array Observations of Coronal Loops and Related Observations of Solar Type Stars", Kenneth R. Lang and Robert F. Willson, 163 Meeting of the American Astronomical Society, Las Vegas, January 9-11, 1984.
6. "Very Large Array Observations of Coronal Loops and Related Observations of Solar Type Stars", Kenneth R. Lang, Union Radio Scientifique International (URSI), Commission J, Special Session on Solar Radio Astronomy, Boulder, January 10-13, 1984.
7. "The Solar-Stellar Connection", Kenneth R. Lang, INDO-US Workshop on Solar-Terrestrial Physics, National Physical Laboratory, New Delhi, India, January 30-February 3, 1984.

8. "Preflare Activity in Solar Active Regions", Kenneth R. Lang and Robert F. Willson, Third Solar Maximum Mission Workshop, Goddard Space Flight Center, February 13-17, 1984.
9. "Short Term Prediction of Solar Bursts - Radio Wavelength Precursors", Kenneth R. Lang, Solar Terrestrial Prediction Workshop, Observatoire de Paris, Meudon, June 18-22, 1984.
10. "VLA Observations of Flare Build Up in Coronal Loops on the Sun and Solar Type Stars", Kenneth R. Lang and Robert F. Willson, Committee on Space Research (COSPAR) - 25th Plenary Meeting, Solar Maximum Analysis, June 25 to July 7, 1984.
11. "VLA Observations of Thermal and Non-Thermal Emission from Coronal Loops", Kenneth R. Lang and Robert F. Willson, 165th Meeting of the American Astronomical Society, Tucson, Arizona, January 13-16, 1985.
12. "Thermal and Non-Thermal Emission from Coronal Plasmas", Kenneth R. Lang, Solar Maximum Mission Topical Meeting on Prominence and Coronal Plasmas, sponsored by SMM-Goddard Space Flight Center, Airlie Conference Center, Warrenton, Virginia, April 9-11, 1985.
13. "Microwave Bursts from Coronal Loops", Kenneth R. Lang and Robert F. Willson, CESRA Workshop on Radio Continua During Solar Flares, Trieste, Italy, Italy, May 27-31, 1985.
14. "High Resolution Observations of the Sun and Nearby Stars", Kenneth R. Lang, Solar Maximum Analysis (SMA) Workshop on Plasma and MHD Physics Applied to Solar Flares, Irkutsk, USSR, June 16-21, 1985.

15. "Microwave Emission from the Sun and Nearby Stars", Kenneth R. Lang, International Astronomical Union (I.A.U.) Joint Discussion on Stellar Activity: Rotation and Magnetic Fields, New Delhi, India, November 19 to 28, 1985.
16. "Coronal Diagnostics - A Review," Kenneth R. Lang, Solar Maximum Mission Topical Meeting on Coronal and Prominence Plasmas, West Virginia, April, 1986.
17. "Coronal Plasmas on the Sun and Nearby Stars," Kenneth R. Lang, Solar Maximum Mission Topical Meeting on Coronal and Prominence Plasmas, West Virginia, April, 1986.
18. "Compact, Variable Moving Sources Observed on the Sun at 2 Centimeters Wavelength," Kenneth R. Lang and Robert F. Willson, Solar Maximum Mission Topical Meeting on Coronal and Prominence Plasmas, West Virginia, April, 1986.
19. "Radio Wavelength Diagnostics of the Solar Corona and the Coronae of Nearby Stars," Kenneth R. Lang, Second CESRA Workshop on Radio Continuum During Solar Flares, Aubigny-Sur-Nere, France, June, 1986.
20. "Radio Wavelength Observations of Magnetic Fields on Active Dwarf M, RS CVn and Magnetic Stars," Kenneth R. Lang, Symposium on Solar and Stellar Activity; XXVI COSPAR (Committee on Space Research) Meeting, Toulouse, France, July, 1986.
21. "Solar Burst Precursors and Energy Build Up at Microwave Wavelengths," Kenneth R. Lang and Robert F. Willson, Symposium on Synopsis of the Solar Maximum Analysis, XXVI COSPAR (Committee on Space Research) Meeting, Toulouse, France, July, 1986.

22. "Simultaneous SMM and VLA Observations of Coronal Loops", Robert F. Willson, Kenneth R. Lang, Kermit L. Smith and Keith T. Strong, paper presented at the 169th meeting of the American Astronomical Society, Pasadena, CA, January, 1987.
23. "Microwave Observations of Solar and Stellar Coronae", Robert F. Willson, presented at the Ninth Sacramento Peak Summer Workshop on Solar and Stellar Coronal Structure and Dynamics, Sacramento Peak Observatory, New Mexico, August, 1987.
24. "VLA - Satellite Observations of the Sun", Kenneth R. Lang, presented at the XXVII Meeting of COSPAR (Committee on Space Research), Helsinki, Finland, July 1988.
25. "High Resolution - VLA and Nancay Observations of the Sun", Kenneth R. Lang, presented at the XXVII Meeting of COSPAR (Committee on Space Research), Helsinki, Finland, July 1988.

VII. VERY LARGE ARRAY OBSERVATIONS CARRIED OUT 1983-1988.

1. CORONAL LOOPS - MAGNETIC STRUCTURE, CYCLOTRON LINES AND THE TRIGGERING AND EVOLUTION OF BURSTS (1983).

Abstract

Recent VLA observations at wavelengths near 20 cm have been used to study the quiescent and burst emission from coronal loops. We propose to amplify and extend these preliminary results by observing coronal loops at five wavelengths between 17.6 cm and 21.7 cm. We will obtain new information on the physics and evolution of coronal loops, the magnetic structure of coronal loops, emission from thermal cyclotron lines, preburst heating, and magnetic changes before and during solar bursts. The optimum B configuration will provide an angular resolution of 2.6 seconds of arc for the entire solar disk. We propose to observe the Sun in the B configuration for 32 hours (8 hours a day) centered at solar transit for four days every other day.

2. SMALL SCALE STRUCTURE AND CYCLOTRON EMISSION FROM SOLAR ACTIVE REGIONS AND SOLAR BURSTS (1983).

Abstract

Our recent VLA observations (in press) indicate the presence of small scale structures, preburst heating and possibly cyclotron emission effects. We propose to use an appropriate gain code with the longer VLA baselines to search for structures with small angular sizes $\theta = 0.1''$ to $4''$ in quiescent active regions and in solar bursts. These observations may be important for future VLBI, VLBA and SOT observations of the Sun. We also propose to use the shorter baselines with a different gain code at several frequencies between 1380 and 1705 MHz in order to simultaneously search for preburst heating and cyclotron line emission in coronal loops. We propose to observe the Sun for 32 hours in the A configuration (8 hours a day centered at solar transit for four days every other day).

3. A SEARCH FOR RADIO EMISSION FROM ACTIVE MAIN SEQUENCE STARS OF LATE SPECTRAL TYPE (1983).

Abstract

We propose a search for radio emission at 6 cm from nearby main sequence stars of late spectral type. The stars exhibit strong evidence for solar type activity, strong magnetic fields, and hot coronae. They include dwarf M flare stars of the UV Cet type, stars whose surface magnetic fields have been measured, stars with active coronae detected at X-ray wavelengths, and stars of the RS CVn type which also emit intense X-ray radiation. Altogether 70 stars will be observed to the 0.5 mJy level (about 30 to 40 minutes).

4. THERMAL GYRORESONANCE VS. NON-THERMAL RADIO EMISSION FROM ACTIVE SOLAR TYPE STARS (1983).

Abstract

We propose to use the VLA to observe the spectrum of the active solar-type star χ^1 Ori, and to search for radio emission from similar stars. The proposed observations will determine the radiation mechanism for these stars, and decide between competing thermal gyroresonance and nonthermal models.

5. VLA OBSERVATIONS OF HIGH ENERGY SOLAR JETS (1984).

Abstract

High resolution rocket observations of the quiet Sun at ultraviolet wavelengths have revealed the presence of energetic, small-scale transient events in the chromosphere and the transition region. We propose 2 cm VLA observations of the quiet Sun that should lead to the detection of these events. Their two-dimensional structure and magnetic field strengths may be determined. New information on the solar granulation, bright points and small ephemeral active regions will also be obtained from the proposed 2 cm observations of the transition region.

6. JOINT VLA - I.U.E. OBSERVATIONS OF FLARE STARS (1984).

Abstract

We propose simultaneous ultraviolet and radio wavelength observations of the nearby dwarf M stars YY Gem, YZ Cmi and AD Leo which are known to emit frequent and powerful flares. The combined observations will determine physical conditions such as electron temperature, electron density and magnetic field strength at a variety of levels in the stellar atmosphere. They will provide valuable new insights to such things as the difference between coronal and chromospheric flares, the flare energy budget, the flare conditions in the transition region and corona, the magnetic field strength and size of the emitter, the response of the stellar atmosphere to nonthermal events, the location of flare energy release, and preburst heating or magnetic changes that may trigger flare emission.

7. COLLABORATIVE MULTIPLE WAVELENGTH OBSERVATIONS OF SOLAR ACTIVE REGIONS (1984).

Abstract

Collaborative multiple wavelength observations of solar active regions are proposed for the RATAN 600, WSRT and VLA telescopes. The combined data will describe the three dimensional structure of solar active regions and resolve a controversy over the radiation mechanism of coronal loops. Radio emission from the legs of magnetic loops will also be observed, and we will attempt to detect thermal cyclotron lines. Observations of solar bursts will include studies of preburst heating, magnetic field changes before and during bursts, and the evolution of solar bursts.

8. VLA OBSERVATIONS OF SLOWLY VARYING EMISSION FROM SOLAR TYPE STARS (1984).

Abstract

Main sequence stars of late spectral type exhibit variable continuum emission that has its origin in active regions in the vicinity of both star spots and chromospheric plage. We propose to observe this emission from both RS CVn and UV Ceti stars at 2 cm, 6 cm and 20 cm wavelength in order to determine the

radiation mechanism and establish the physical properties of the emitter. Electron temperatures, emission measures and magnetic field strengths will be inferred. This will provide valuable information about the star spots and surface plage of solar-type stars. We will also attempt to observe thermal cyclotron lines from the RS CVn stars.

9. VLA OBSERVATIONS OF THE INNER SOLAR CORONA AT 21 CM and 91 CM WAVELENGTH (1985).

Abstract

VLA observations at 21 and 92 cm will bridge the gap between the visible solar surface and the outer solar corona. They will provide high angular resolution measurements ($> 6''$ at 327 MHz) of Type I or Type III bursts thereby resolving uncertainties over whether they are located at the top or legs of magnetic loops or in open fields lines. Changing magnetic structures related to these bursts will also be detected. The early stages, driving mechanism and initiating sources of coronal transients or mass ejections, may also be described. We will continue our search for thermal cyclotron lines and coordinate our observations with the SMM and P 78-1 satellites as well as with the K-coronameter at Mauna Loa.

10. MULTIPLE WAVELENGTH OBSERVATIONS OF M DWARF FLARE STARS AND RS CVN STARS (1985).

Abstract

We propose to use the VLA to observe six M dwarf flare stars and two RS CVn stars at 2, 6 and 20 cm wavelength. Our observations of flare stars will be used to search for impulsive and longer-term variations which occur at different heights in stellar atmospheres. Observations of RS CVn stars will be made with 3.3 second resolution in an attempt to detect impulsive events which may be superimposed on more gradual bursts.

11. COORDINATED VLA AND SOLAR MAXIMUM MISSION OBSERVATIONS OF SOLAR MASER BURST EMISSION AND CYCLOTRON LINE EMISSION (1985).

Abstract

The VLA will be used in coordination with the Solar Maximum Mission X-ray satellite to study narrow-band maser burst emission and cyclotron line emission from the Sun. The combined data will be used to determine the location and structure of maser emission and to test theories of coronal heating by maser spikes during bursts. Observations of cyclotron line emission near 20 cm wavelength in combination with soft X-ray observations will lead to estimates of the magnetic field strengths, electron density and electron temperature in coronal loops during quiet periods and before bursts. All of these observations will provide constraints to theoretical models of solar eruptions in which a coronal loop is heated, becomes unstable and then erupts, giving rise to impulsive bursts.

12. VLA OBSERVATIONS SIMULTANEOUS WITH BALLOON OBSERVATIONS OF SOLAR HARD X-RAY MICROWAVE BURSTS (1985).

Abstract

Sensitive balloon-borne hard X-ray spectrometer instrumentation has revealed very small hard X-ray bursts termed microflares. The microflares last from a few seconds to ten seconds, and they have a power law spectrum with the number of events increasing with decreasing flux. Such a spectrum suggests a nonthermal emission mechanism. The proposed VLA - hard X-ray balloon observations are designed to test the spectral nature of the microbursts and to also test the hypothesis that they may collectively contribute significantly to the heating of the solar corona.

13. VLA OBSERVATIONS OF COMPACT, TRANSIENT SOURCES ON THE SUN (1986).

Abstract:

Recent VLA solar observations at 2 cm wavelength have revealed the presence of compact ($\theta \sim 5''$), transient (lifetimes $\tau < 30$ and > 90 s), highly circularly polarized ($\rho_c \sim 80-90\%$) sources in regions of weak magnetic fields ($H < 80$ Gauss). The brightness temperatures of $T_B \sim 10^5$ K are comparable to those found in the transition region. Here we propose 12 continuous hours of observing this entirely new class of solar radio sources using the D configuration for both quiet and active regions on the Sun. Simultaneous observations at the Big Bear Solar Observatory may establish a connection between the compact, transient 2 cm sources and ephemeral magnetic regions seen in the photosphere. The temperatures, sizes and lifetimes of the 2 cm sources are also comparable to those of ultraviolet brightenings in active regions, and simultaneous SMM observations will be arranged.

14. SIMULTANEOUS VLA SMM OBSERVATIONS OF THE INNER SOLAR CORONA (1986).

Abstract:

The quiescent, or non-flaring, radiation and solar bursts from coronal loops in the inner solar corona will be simultaneously observed with the VLA and the SMM satellite. VLA observations of quiescent emission at 20 cm wavelength will provide estimates of electron temperature and electron density (thermal bremsstrahlung or gyroresonance radiation) and magnetic field strength (thermal cyclotron lines). Simultaneous SMM soft X-ray (XRP) observations will provide independent values for electron temperature and density during quiescent periods and during preburst heating. The VLA 20 cm observations will also provide information on the preburst heating, magnetic triggering and narrow-band features of solar bursts. If the 92 cm system is operational, we will also specify the size and location of the initiating source for decimetric bursts for the first time.

15. SIMULTANEOUS VLA AND OVRO OBSERVATIONS OF SOLAR ACTIVE REGIONS (1986).

Abstract

We propose simultaneous observations of solar active regions with the VLA at 2, 6 and 20 cm and with the OVRO frequency-agile interferometer (3 elements) at 50 wavelengths between 1.8 and 30 cm. The combined data will enhance the scientific return beyond that expected by using either instrument alone. The VLA will provide angular resolution and structural information that are limited by the incomplete U-V coverage of the OVRO system. In contrast, the OVRO data will provide complete spectral information that cannot be obtained at the VLA.

16. VLA OBSERVATIONS OF THE SUN AT 92 CM AND 20 CM WAVELENGTH (1986).

Abstract

Our recent VLA map of the Sun at 92 cm wavelength led to the discovery of bright (10^6 K), highly circularly polarized (90%) features that could not have been resolved with any other instrument. Here we propose mapping the entire solar disc at this wavelength (92 cm) with hitherto unavailable angular resolution. Comparisons will be made with 92 cm maps at Nancay (larger scale features), a full disk VLA 20 cm map (lower-lying loops), and SMM soft X-ray maps (physical parameters like electron density and temperature).

17. A SEARCH FOR MICROWAVE RADIATION FROM MAGNETIC STARS (1986).

Abstract

We propose a search for microwave emission from 22 magnetic stars during 33 consecutive hours of VLA observations. These stars have intense dipolar magnetic fields and hot, dense coronal electrons. The thermal electrons will produce gyroresonant, or cyclotron, radiation that is detectable with the VLA. The observed total intensity and circular polarization will provide values for the coronal magnetic field strength and the angle between the line of sight and the dipolar axis. Variations in these quantities can be inferred from the variable microwave emission, thereby testing the oblique rotator model for magnetic stars.

18. MULTIPLE WAVELENGTH OBSERVATIONS OF DWARF M FLARE STARS (1986).

Abstract

Our recent VLA observations of YZ Cmi near 1420 MHz have revealed narrow-band frequency structure (less than 100 MHz) in the slowly-varying quiescent radiation. The mere detection of this radiation rules out gyroresonant emission, and the narrow-band structure rules out thermal bremsstrahlung, gyroresonant emission, and gyrosynchrotron radiation. Coherent emission processes seem to be required. Here we propose multiple-wavelength (near 1420 MHz) observations of YZ Cmi, UV Ceti, YY Gem and Wolf 630. We will confirm and elaborate our conclusions for YZ Cmi and extend them to three other dwarf M stars. A byproduct of the proposed observations (6 hours per star) will be the detection of stellar bursts and conclusion about their possible coherent nature.

19. A VLA SURVEY OF ACTIVE BY DRACONIS AND W URSAE MAJORIS STARS (1987).

Abstract

We will extend VLA observations of main sequence (dwarf) stars from the dwarf M stars to active dwarf stars of spectral type F, G or K. Twenty-one stars of the BY Dranconis (starspots) or W Ursae Majoris (contact binary) types will be observed for one hour each at 4835, 4885, 1415 and 1515 MHz, providing detection thresholds of about 0.3 mJy. The candidate stars all emit intense X-ray radiation and strong ultraviolet lines; some of them also exhibit evidence for strong photospheric magnetic fields. The detection of microwave radiation from these stars will enable direct measurements of the coronal magnetic fields that must constrain the X-ray emitting plasma. Spectral information, circular polarization and narrow-band features will provide important constraints to the radiation mechanism and possible evidence for coherent processes. The extension of VLA observations from dwarf M stars to dwarfs of spectral class F, G, or K will also have important implications for studies of stellar evolution and stellar structure.

20. VLA OBSERVATIONS OF STELLAR BREMSSTRAHLUNG FROM CAPELLA AND VW CEPHEI (1987).

Abstract

Although the microwave radiation from binary stars is usually explained by nonthermal processes, the 6-cm radiation from two binary systems has been attributed to the thermal bremsstrahlung of their X-ray emitting plasma. They are the long-period Capella system and the short-period eclipsing binary VW Cephei. However, no circular polarization information was given, and the emission was observed at only one wavelength. Here we propose multiple-wavelength VLA observations of these two stellar systems at 2, 6 and 20 cm wavelength in order to test the thermal radiation hypothesis. The proposed observations may also provide evidence for nonthermal emission mechanisms such as gyrosynchrotron radiation or coherent processes.

21. SIMULTANEOUS VLA AND IUE OBSERVATIONS OF THE CONTACT BINARY VW CEPHEI (1987).

Abstract

Previous microwave observations of the contact binary VW Cephei have been limited to a single wavelength, and the binary system has not been monitored over a full orbital period (6.7 hours) at either ultraviolet or microwave wavelengths. Here we propose VLA observations of VW Cephei over two orbital periods (14 hours) at 2 cm, 6 cm and 20 cm wavelength. Simultaneous observations with the IUE satellite will monitor ultraviolet activity during 8 of these 14 hours. The proposed observations will provide evidence for radiation from the surface of one active star and/or from a hot plasma that envelops the two stars. We will also obtain spectral data and circular polarization information that will test different radiation mechanisms, including the hypothesis that the microwave emission is the thermal radiation of the X-ray emitting plasma.

22. SIMULTANEOUS SMM AND VLA OBSERVATIONS OF CORONAL LOOPS (1987).

Abstract

We propose simultaneous observations of both quiescent emission and solar bursts from coronal loops at X-ray (SMM) and 20 cm (VLA) wavelengths. The proposed observations continue a rewarding series of VLA probes of coronal loops. We will establish the dominant radiation mechanisms in the two spectral regions. Plasma parameters will be inferred from X-ray spectral lines and from microwave polarization and temperature data. Thermal cyclotron lines, current-amplified magnetic fields, the coronal magnetic field, preburst heating, and the magnetic triggering of solar bursts will also be investigated.

23. MULTIPLE WAVELENGTH VLA OBSERVATIONS OF COMPACT TRANSIENT SOURCES ON THE SUN (1987).

Abstract

Recent VLA solar observations at 2 cm wavelength have revealed the presence of compact ($\theta \sim 5''$), transient (lifetimes $\tau \sim 30$ s) highly circularly polarized ($\rho_c \sim 80-90\%$) sources in regions of weak magnetic fields ($H \leq 100$ G). The brightness temperatures of $T_B \sim 10^5$ K are comparable to those found in the transition region. Here we propose 16 observing hours of this new class of solar radio sources using the B configuration at 2, 6 and 20 cm wavelength. Simultaneous observations at these three wavelengths should help to establish the radiation mechanism of these sources. Comparisons with optical data may also establish a connection between the compact sources and ephemeral magnetic regions seen in the photosphere, while comparisons with the Solar Maximum Mission Satellite may provide a connection with coronal bright points.

24. SIMULTANEOUS VLA AND OVRO OBSERVATIONS OF SOLAR ACTIVE REGIONS (1987).

Abstract

We propose simultaneous observations of solar active regions with the VLA at 2, 6 and 20 cm and with the OVRO frequency-agile interferometer (3 elements) at 50 wavelengths between 1.8 and 30 cm. The combined data will enhance the scientific return beyond that expected by using either instrument alone. The VLA will provide angular resolution and structural information that are limited by the incomplete U-V coverage of the OVRO system. In contrast, the OVRO data will provide complete spectral information that cannot be obtained at the VLA.

25. A VLA SURVEY OF COOL STARS (1987).

Abstract

Microwave observations of cool main sequence stars are currently limited to the dwarf M stars. Here we propose a VLA survey of seventy two (72) nearby active stars of spectral type F, G, and K. These stars all exhibit chromospheric activity, and most of them emit intense X-ray radiation. Many of them rotate much faster than the Sun, and several of them have strong photospheric magnetic fields. The proposed VLA survey will lead to direct measurements of the coronal magnetic fields while also establishing correlations between microwave radiation and other stellar properties such as mass, rotation rate, spectral type, binarity, X-ray luminosity and chromospheric activity. Altogether, forty-eight (48) continuous hours are requested, with 30 to 40 minutes per star at 4835, 4885, 1415 and 1515 MHz.

26. EVOLUTION OF CORONAL LOOPS AT 20 CM AND 90 CM WAVELENGTH (1988).

Abstract

We propose to map the entire Sun at 20 cm and 90 cm on 4 days, covering a period of about a week. Comparisons will be made with 164 cm maps (made at Nancay) in order to study the evolution and three dimensional structure of large-scale coronal loops previously detected at 92 cm. These observations will also provide information about solar noise storms and the mechanism that triggers them.

27. VLA OBSERVATIONS OF THE DYNAMIC SPECTRA OF BURSTS FROM THE ACTIVE STARS YZ CMi, WOLF 424 and BY DRACONIS (1988).

Abstract

We propose spectral-line mode observations of YZ Cmi, Wolf 424 and By Draconis that are designed to measure the dynamic spectra of microwave bursts from these stars. The detection of narrow-band burst emission requires a coherent radiation mechanism and provides important constraints on the magnetic fields and the electron density in the stellar coronae.

28. SIMULTANEOUS VLA - NANCAY RADIOHELIOGRAPH OBSERVATIONS OF THE SUN (1988).

Abstract

We propose observations of the Sun during the 3 hours that it is simultaneously visible with the VLA and the Nancay Radioheliograph (NR). Both the quiet and active Sun will be investigated by combining the high angular resolution of the VLA at 328 MHz with the good angular resolution of the NR at 164 MHz, the high time resolution of the NR (0.2 seconds), and the multiple-frequency capability of the NR (up to five frequencies). The combined data will be used to study the large-scale magnetic loops that determine the global magnetic structure of the quiet corona. They will also provide new information about solar noise storms, decimetric pulsations, coherent burst processes, Type II and III bursts, and coronal mass ejections.

VIII. DESCRIPTION OF RESEARCH FACILITIES

We have observed solar activity from 1983 to 1988 using the Very Large Array (VLA), the Solar Maximum Mission (SMM) satellite and the Nancay Radioheliograph. Grant AFOSR-83-0019 has provided salary support to two scientists at Tufts University who have carried out these observations and promptly published the results (see Section X: Appendix). The unique observational facilities have been provided at no additional cost to the United States Air Force. They are the largest, most-powerful instruments available; costing hundreds of millions of dollars to construct and operate.

The Very Large Array is a system of 27 antennae with individual diameters of 25 meters (82 feet) spread across a desert in New Mexico at separations as large as 34 kilometers (21 miles). The antennae are all interconnected electronically to provide a total of 356 interferometer pairs, and a combined angular resolution of about one second of arc (one 3,600th of a degree and about one ten millionth the surface area of the Sun). Signals can be recorded every three seconds of time in four different ways (the four Stokes parameters) at each antenna, and the combined signals from all 27 antennae can be used to obtain six hundred thousand pieces of information every hour. The VLA is operated at an annual cost of 10 million dollars by the National Science Foundation with no cost to the Air Force. It is the only such telescope in the world.

We have also carried out simultaneous observations of solar activity with the Solar Maximum Mission (SMM) satellite at X-ray wavelengths. Data taken with this 75-million-dollar spacecraft were also provided at no additional cost to the Air Force. Both the soft X-ray Polychromater (XRP) and the hard X-ray burst spectrometer (HXRBS) were used to obtain unique, simultaneous X-ray observations of solar activity. The angular resolution and field of view of these instruments were comparable to those obtained with the VLA. Of course, the X-ray observations can only be carried out from satellites that have been lofted above the Earth's absorbing atmosphere.

Simultaneous observations of solar activity were also carried out with the Nancay Radioheliograph. This solar-dedicated facility is a system of 42 antennae with individual diameters of up to 10 meters spread across separations as large as 3.2 kilometers, providing a total of 55 interferometer pairs that sample total intensity and circular polarization at up to five wavelengths with arbitrary separations at time intervals as short as 20 milliseconds. The costs of obtaining this data and analyzing it in the relevant computers were provided by the French government with no cost to the United States Air Force.

Each of our observations took advantage of the unique capabilities of the three systems. The VLA was used to obtain the high second-of-arc angular resolution required to resolve solar microwave structures. It is the only telescope in the world that can provide this angular resolution. The SMM satellite is similarly unique in its ability to carry out supporting high-angular-resolution observations of solar activity at X-ray wavelengths, while the Nancay instrument uniquely provided high resolution in both frequency and time. Moreover, the combined observations with all three systems enhanced the scientific return beyond that which would have resulted if any one of them were used alone.

In other words, the Air Force obtained some extraordinarily unique data in a very cost-effective manner. The major portion of the cost of obtaining the VLA, SMM, and Nancay data was met by other institutions. Grant AFOSR-83-0019 has provided salaries and travel costs of the scientists that analyzed and compared the data, thereby producing a high scientific return at relatively low cost.

IX. RELEVANCE OF RESEARCH TO THE UNITED STATES AIR FORCE

The research carried out under the support of grant AFOSR-83-0019 has provided new perspectives to the origin and prediction of powerful explosions that erupt from solar active regions. Our studies of coronal magnetic fields, plasma emission processes and particle acceleration have led to new insights about the origin and evolution of these explosions. Our observations of preburst heating and magnetic triggering in coronal loops may, for example, lead to reliable predictions and warnings of solar explosions on time scales of tens of minutes to hours. At longer wavelengths, new information has been obtained about solar noise storms, the most frequent type of solar activity, as well as the unknown initiating mechanisms for other types of solar bursts or flares. All of these explosive phenomena generate energetic particles that travel to the near-Earth environment where they can interfere with surveillance operations, disrupt tracking communications, and degrade or endanger high-flying aircraft, missiles, or satellites. It is for these reasons that the proposed observations of solar activity are of direct practical interest to the Air Force.

Observations of solar active regions with the Very Large Array (VLA) under the support of grant AFOSR-83-0019 have led to many new discoveries about solar activity. They include the discoveries of compact, transient heating sources, the microwave counterparts of coronal loops, thermal cyclotron lines, large-scale magnetic loops, and the sources of solar noise storms, as well as evidence for preburst heating, magnetic triggering and coherent radiation mechanisms. These results have important implications for forecasting and understanding solar activity that may directly endanger high-flying spacecraft or disrupt communications with them.

X. APPENDIX - REPRINTS OF PAPERS PUBLISHED 1983 to 1988.

The reprints of the thirty-eight (38) papers published under the support of grant AFOSR-83-0019 have been bound together and submitted under separate cover at the same time as this final technical report.